Université de Montréal

Marais de saules à effluent nul pour le traitement d’eau contaminée

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Thèse présentée en vue de l’obtention du grade de
docteure en sciences biologiques

Novembre, 2019

Université de Montréal

Département de sciences biologiques, Faculté de arts et des sciences

Cette thèse intitulée :

Marais de saules à effluent nul pour le traitement d'eau contaminée

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Résumé

Au cours des dernières décennies, un type de marais filtrant, généralement planté de saules, a été développé pour opérer un système de traitement d'eau sans effluent, par évapotranspiration. Ces marais à effluent sont généralement utilisés pour le traitement d'eau usée domestique, mais pourraient aussi présenter une alternative intéressante pour d'autres applications, comme le traitement de lixiviat contaminé. Les guides de conception actuellement disponibles ne permettent toutefois pas de concevoir un système flexible qui permettrait de gérer les grandes variations de volume à traiter liées à la nature même des lixiviats (*i.e.* résultent entièrement des précipitations) et ne tiennent pas compte de la variation inter et intra-annuelle de l'évapotranspiration (ET) du saule.

Cette thèse présente d'abord une revue de littérature de ET du genre *Salix* et de ses facteurs de variation les plus importants. Il apparaît que les conditions de croissance ont plus d'importance que l'identité spécifique et que la disponibilité en eau, la fertilisation et la contamination sont les principaux facteurs dictant l'ET des saules. L'effet de l'âge, du contexte expérimental, de la densité de plant et du type de sol n'a pas pu être clairement démontrés par cette revue. Ensuite, une étude portant sur le potentiel d'ET de *S. miyabeana* 'SX67' est présentée. Il est démontré qu'un modèle basé sur des paramètres foliaires et sur le déficit de pression de vapeur d'eau dans l'air permet de prédire l'ET de *S. miyabeana* en condition de marais filtrant. Cette étude permettra entre autres d'améliorer les plans de conception d'un éventuel marais de saules à effluent nul. Pour continuer, la réponse de *S. miyabeana* 'SX67' à différentes concentrations de lixiviat et à différents types de substrats a été étudiée. Ce cultivar s'est montré tolérant aux concentrations du lixiviat brut retrouvées sur un site d’entreposage de poteaux de bois traité. Le type de substrat a influencé la réponse du saule et ses performances écophysiologiques, en plus d’affecter la dynamique des contaminants. Finalement, la modélisation hydrologique d’un système à effluent nul par marais de saules permet de proposer une méthode de dimensionnement des différents compartiments du système pour atteindre un objectif d’effluent nul sur une période de 20 ans, ainsi que de proposer des solutions de conception et d’opération optimale. L’application du modèle au cas spécifique d’un site d’entreposage de poteaux de bois traité a permis d’évaluer la faisabilité, d’un point de vue hydrologique, de cette technologie dans le contexte climatique du sud du Québec.

Sur la base de cette étude, la principale limite pour l’application des marais à effluent nul au Québec sont la surface de marais et le volume de stockage requis. Dans le cas où une étape de prétraitement efficace précède le marais de saule, la durée de vie du marais ne devrait pas être limitante et dépendra principalement de la durée de vie des végétaux. Cependant, le destin des contaminants dans le système, qu’il s’agisse de la disposition des contaminants accumulés à l’étape de prétraitement ou d’une éventuelle translocation de contaminants dans les parties aériennes des végétaux, devrait être considéré avant d’établir un système à effluent nul. Les résultats de cette recherche permettent, entre autres, de proposer les marais de saules à effluent nul comme une alternative intéressante pour le traitement d’eau contaminée au Québec.

Mots-clés : marais évapotranspirant, marais à effluent nul, phytotechnologie, traitement de lixiviat, évapotranspiration, génie écologique

Abstract

During the last decades, a type of constructed wetlands, usually planted with willows, was developed to operate a water treatment system with zero effluent, by evapotranspiration. These zero liquid discharge wetlands are typically used for domestic wastewater treatment, but could also be an attractive alternative for other applications, such as contaminated leachate treatment. However, the design guidelines currently available do not allow for the design of a flexible system that would manage the large variations of volume to be treated related to the very nature of leachates (*i.e.* produced entirely from precipitation) and do not take into account inter and intra-annual variation of willows evapotranspiration (ET).

This thesis first presents a literature review of ET for the genus Salix and its most important driving factors. It appears that growing conditions are more important than species identity and that water availability, fertilization and contamination are the main factors dictating ET in willow. The effect of age, experimental context, planting density, and soil type could not be clearly demonstrated by this review. Then, a study on the potential ET of *S. miyabeana* 'SX67' is presented. It is shown that a model based on foliar parameters and on the water vapor pressure deficit in the air makes it possible to predict the ET of *S. miyabeana* under wetland conditions. This study will, among other things, improve the design plans for a potential zero effluent willow wetland. To continue, the response of *S. miyabeana* 'SX67' to different leachate concentrations and different types of substrates was studied. This cultivar has been tolerant of raw leachate concentrations found at a treated wood pole storage site. The type of substrate influenced the willow response and ecophysiological performance, and affected the dynamics of the contaminants. Finally, the hydrological modelling of a system with zero effluent by willow bed makes it possible to propose a method of dimensioning for the different compartments of the system in order to reach a zero effluent objective over a period of 20 years, as well as to propose solutions for optimal design and operation. The application of the model to the specific case of a treated wood pole storage site made it possible to assess the hydrological feasibility of this technology in the climate context of southern Quebec.

On the basis of this study, the main limit for the application of zero effluent willow bed in Quebec is the wetland area and the storage volume required. In the case where an effective pre-treatment step precedes the willow bed, the life of the wetland should not be limiting and will depend mainly on the lifespan of the plants. However, the fate of the contaminants in the system, be it the disposition of the accumulated contaminants at the pre-treatment stage or a possible translocation of contaminants into the aerial parts of the plants, should be considered before establishing a system with zero effluent. The results of this research make it possible, among other things, to propose zero-effluent willow wetlands as an interesting alternative for the treatment of contaminated water in Quebec.

Key words: evapotranspiration wetland, zero discharge wetland, phytotechnology, leachate treatment, willow evapotranspiration, ecological engineering

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Liste des symboles

3,5-DCP	3,5-dichlorophénol
ΔL	Variation de niveau
Θ	Porosité
Δ	Pente de la courbe de pression de vapeur
υ_2	Vitesse du vent (m/s) à 2 mètres du sol
γ	Constante psychrométrique
α_{inter}	Variation interspécifique
α_{intra}	Variation intraspécifique
A_{leaf}	Surface d'une feuille
$A_{wetland}$	Surface du marais
ACC	Arséniate de cuivre chromaté
ATSDR	Agency for toxic substance and disease registry
BEP	Bassin d'entreposage des poteaux
CCA	Chromated chromium arsenate
CO	Composés organiques
CP	Chlorophénols
Cr^{3+}, Cr^{6+}	Chrome trivalent/hexavalent

d	Day
DCO	Demande chimique en oxygène
e_a	Pression de vapeur réelle
e_s	Pression de vapeur saturante
EC_{50}	La concentration efficace médiane
ET	Evapotranspiration
ET_0	Evapotranspiration de référence
E_s	Évaporation du sol
ET_{SX67}	Évapotranspiration de *Salix miyabeana* 'SX67'
ET_{wet}	Évapotranspiration du marais
ET cover	Evapotranspiration cover (*i.e.* plantation aimed at intercepting rainfall and reducing leaching)
G	Densité de flux de chaleur du sol
$\bar{g}_s$	Conductance stomatique ponctuelle
$\bar{G}_s$	Conductance stomatique générale/moyenne
HxCDD/Fs	Hexachloro dibenzo-dioxines/furanes
HpCDD/Fs	Heptachloro dibenzo-dioxines/furanes
I	Pourcentage d'interception des précipitations par la canopée
IRBV	Institut de recherche en biologie végétale
K_c, K_{et}	Coefficient de plant

Log K_{ow}	Coefficient octanol:eau
L	Water level
LA	Surface foliaire
LAI	Indice de surface foliaire
LAI_{active}	Indice de surface foliaire capable de transpirer
LA_w	Surface foliaire d'un saule
MDDELCC	Ministère du développement durable, de l'environnement et de la lutte aux changements climatiques
MF	Marais filtrant(s)
MS	Marais de saule
N_{leaf}	Nombre de feuilles
NH^{4+}	Ammonium
NO_3	Nitrate
NTP	National toxicology programm
OcCDD/Fs	Octachloro dibenzo-dioxines/furanes
ORP	Potentiel d'oxydo-réduction
PCDD/Fs	Polychloro dibenzo-dioxines/furanes
PCP	Pentachlorophénol
PeCDD/Fs	Pentachloro dibenzo-dioxines/furanes
pET	Évapotranspiration potentielle

POPs	Polluants organiques persistants
pRG	Taux de croissance proportionnel
Ps	Photosynthèse
Q_d	Taux de drainage
Q_i	Taux d’entrée
Q_o	Taux de de sortie
Q_p	Taux de précipitation
Q_r	Taux de ruissellement
r^2	Coefficient de détermination
R_n	Rayonnement net à la surface de la culture
SEN	Système à effluent nul
T	Température
TeCDD/Fs	Tetrachloro dibenzo-dioxines/furanes
TEQ	Équivalent toxique
TF	Translocation factor
VPD	Déficit de pression de vapeur d’eau
WHO	World health organisation
ZLD	Zero-liquid discharge
ZDWs	Zero-discharge wetlands

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Remerciements

La réalisation de ce projet de recherche n'aurait pas été possible sans la contribution des plusieurs acteurs. Je remercie d'abord mes directeurs, Jacques Brisson et Yves Comeau, d'avoir eu confiance en moi tout au long de ce projet et de m'avoir conseillé et épaulé dans mes différentes tâches, notamment la rédaction de mes articles et de cette thèse. Je remercie particulièrement le professeur Brisson de m'avoir fourni un encadrement exemplaire, et des possibilités d'épanouissement professionnel incroyables. Je remercie aussi les membres d'Hydro-Québec impliqués dans la chaire de recherche pour leur support, particulièrement Chantale Gaudreault et André Gauvreau qui m'ont assisté techniquement tout au long du projet. J'aimerais aussi par ailleurs souligner le soutien technique de la firme Enviro-Services. Finalement, je remercie sincèrement tous mes collègues, étudiants, assistants-techniques, stagiaires et professionnels de recherche qui ont fait de mon parcours une expérience amusante, riche et stimulante. Un merci spécial à Sabrina Demers-Thibeault, Patrick Boivin, Benoît St-Georges et Yannika Poirier-Martin sans qui la réussite de ce projet n'aurait pas été possible. Finalement, j'aimerais remercier mon conjoint, dont le support moral m'a permis de traverser plusieurs épreuves personnelles tout au long de mon parcours.

Chapitre 1 | Introduction

1.1 Traitement d'eau contaminée

1.1.1 Source et type de contamination

La contamination de l'eau constitue une problématique environnementale et de santé publique généralisée et imputable à divers secteurs d'activités anthropiques. Quelle que soit la source et la nature de la contamination d'un effluent, il est attendu que celui-ci soit préalablement traité avant d'être rejeté à l'environnement. On distingue généralement trois grandes catégories d'eaux usées, soit les effluents domestiques, agricoles et industriels. Les eaux usées domestiques proviennent de ménages résidentiels et autres établissements (*e.g.* écoles, restaurants, hôpitaux) et sont constituées des eaux grises, provenant de l'utilisation d'une douche ou d'une machine à laver, par exemple, et des eaux noires (incluant les eaux jaunes), provenant des cabinets de toilettes. Ces eaux peuvent être collectées et traitées par un réseau municipal ou encore traitées sur place, dans le cas d'installations isolées, par différents types de systèmes individuels (traitement décentralisé). Les effluents domestiques sont caractérisés par la présence d'azote, de phosphore, de pathogènes et d'autres contaminants dits émergents tels que des produits pharmaceutiques ou des molécules perturbatrices des systèmes endocriniens (Nakada e*t al.*, 2006). Les eaux usées agricoles proviennent notamment des déjections animales, et du nettoyage des installations (planchers, matériel de traite, etc.), mais n'incluent pas les eaux de ruissellement des terres agricoles. Elles sont généralement très riches en phosphore et en azote, mais aussi souvent en ammonium, produits pharmaceutiques, pesticides et autres produits chimiques (Cicek, 2003).

Finalement, les eaux usées industrielles peuvent contenir une multitude de contaminants dépendamment du type d'industrie, et être produites directement par un processus industriel ou encore provenir de la lixiviation de différents composants d'origine industrielle. On peut aussi inclure dans cette catégorie les différentes sources de contamination des eaux de ruissellement, tels les hydrocarbures et les sels de déglaçage issus du secteur du transport. Citons à titre de source industrielle de contamination de l'eau les effluents de raffineries contenant plusieurs composés organiques toxiques (Diya'uddeen *et al*., 2011), des effluents contenant des polluants employés dans des procédés de fabrication comme les pâtes et papiers (Pokhrel & Viraraghavan, 2004) et dans l'industrie agroalimentaire (Lefebvre & Moletta, 2006), ou encore l'industrie textile générant dans l'environnement des teintures potentiellement mutagènes (Carneiro *et al*., 2010). Les problèmes dus à la lixiviation des contaminants sont souvent rencontrés dans le secteur minier, sous la forme des drainages miniers acides contenant notamment des cyanures et des métaux lourds (Akcil & Kolda, 2006), des sites d'enfouissement, avec des lixiviats aux pH extrêmes et souvent riches en chlorures, sulfates et ammonium (Keenan *et al*., 1984), et de l'industrie de la préservation du bois qui utilise entre autres des contaminants organiques polychlorés et des métaux lourds (Kitunen *et al*., 1987; Bhattacharya *et al*., 2002).

Tel qu'évoqué précédemment, les types de contaminants pouvant être retournés dans les eaux usées sont très nombreux. On distingue les contaminants chimiques de ceux dits biologiques comme les virus et bactéries, et on peut les classer selon deux grandes catégories, soit les contaminants organiques et inorganiques. Les composés organiques (CO) ont une base chimique carbonée et regroupent des classes de contaminants tels les hydrocarbures, les pesticides et les produits pharmaceutiques. Les CO peuvent être dégradés en molécules plus simples et potentiellement inoffensives, bien que la rapidité et l'efficacité de ce processus dépendent grandement de la nature du composé. Certains, comme les produits organiques persistants (POPs), sont très persistants dans l'environnement. Les contaminants inorganiques comprennent les métaux lourds et métalloïdes, et autres molécules solubles tels les chlorures. Ils ne peuvent pas être dégradés et requièrent donc un traitement différent des contaminants organiques. Bien que non toxiques en général, d'autres paramètres dont les composés azotés comme les nitrates (NO_3), les matières en suspension (MES) et la demande chimique en oxygène (DCO) sont considérés comme des contaminants lorsque leur concentration est élevée au point d'avoir un impact néfaste sur l'environnement ou la santé humaine. Les contaminants émergents regroupent toutes sortes de polluants, pour la plupart organiques, dont l'étude et le traçage est relativement récent et parfois fastidieux en raison de contraintes techniques. On pense notamment aux composés hormonaux, aux retardateurs de flammes et aux surfactants.

1.1.2 Méthodes de traitement

Le traitement des eaux usées comprend généralement plusieurs étapes (Tableau 1), déterminées selon la nature des eaux usées et les moyens disponibles. Par exemple, le traitement des eaux usées domestiques comprend généralement les étapes de traitement préliminaire, primaire et secondaire et les techniques employées sont très standardisées à un niveau régional. Un traitement tertiaire ou avancé comme la désinfection et le retrait de l'azote et du phosphore est parfois ajouté dans les grands centres urbains disposant des moyens financiers nécessaires à l'implantation et l'opération des équipements requis. Les étapes du traitement d'autres types d'eaux usées dépendent principalement des exigences de rejet en vigueur et des caractéristiques de l'effluent à traiter. Dans certains cas d'effluent industriels, un traitement avancé spécifique peut même constituer la seule étape de traitement (Drinan and Spellman, 2013).

Tableau 1.1 Étapes typiques du traitement des eaux usées, ainsi que leurs objectifs respectifs et les types de processus pouvant être utilisés (Drinan and Spellman, 2013; Nesaratnam, 2014)

Type de traitement	**Objectif du traitement**	**Types de processus**
Préliminaire	Retrait ou broyage des gros objets	Physique
Primaire	Retrait de la majorité des particules fines, d'une partie de la matière en suspension et réduction de la demande biologique en oxygène	Physique et chimique
Secondaire	Réduction de la matière en suspension et de la demande biologique en oxygène à 30 mg/L ou moins	Physique, chimique et/ou biologique
Tertiaire	Réduction supplémentaire de la matière en suspension et de la demande biologique en oxygène, retrait de polluants comme l'azote et le phosphore et/ou les métaux lourds	Physique, chimique et/ou biologique
Avancé	Retrait de contaminants organiques traces, de pathogènes, ou tout autre contaminant spécifique et problématique	Physique, chimique et/ou biologique

Alors que les techniques de traitement préliminaire et primaire varient peu, les techniques de traitement secondaire, tertiaire et avancé sont nombreuses. Parmi ces techniques, les phytotechnologies telles que les marais filtrants sont désormais reconnues comme une approche permettant de traiter plusieurs types d'effluents *in situ* (Bavor *et al.*, 1995; Vymazal, 2010; Martinez-Guerra *et al.*, 2015). Dans de tels marais, les macrophytes et la microfaune associée à leur système racinaire permettent la dégradation de certains contaminants organiques et/ou l'immobilisation, voire même la translocation, d'éléments traces métalliques. Les marais peuvent donc être utilisés tant au niveau du traitement secondaire que tertiaire ou avancé, dépendamment de leur conception; on peut, par ailleurs, les utiliser en combinaison pour remplir différents objectifs. Les marais filtrants offrent plusieurs avantages, en regard d'autres technologies « traditionnelles », dont le traitement *in situ*, des coûts d'installation et d'entretien relativement faibles, une faible consommation énergétique et une grande acceptabilité sociale.

1.1.3 Défis du traitement d'eau contaminée

Quelle que soit la technologie de traitement d'eau utilisée, il peut s'avérer ardu de satisfaire les critères environnementaux établis par les gouvernements. L'efficacité des marais filtrants est notamment limitée par leur sensibilité aux conditions environnementales et par la présence de molécules particulièrement difficiles à dégrader (Campanella *et al.*, 2002). Certains effluents, comme les lixiviats, sont complexes et contiennent d'innombrables combinaisons de contaminants, expliquant que les méthodes de traitement soient rarement sans faille et qu'il n'existe à ce jour aucune solution universelle de traitement des lixiviats (Wiszniowski *et al.*, 2006). Il est donc attendu qu'il subsistera toujours une certaine contamination suite au traitement et les objectifs d'efficacité sont basés sur les normes gouvernementales en vigueur. Or, certaines de ces normes sont établies en fonction de la toxicité des polluants et peuvent donc s'avérer très contraignantes dans le cas de polluants hautement toxiques, comme les dioxines et les furanes, par exemple (U.S. EPA, 2006a). Dans le cas du traitement d'eau usée domestique, le phosphore demeure un élément difficile à retirer complètement, alors que les normes de rejets à respecter sont, elles, de plus en plus sévères. La contamination résiduelle est aussi un problème dans des secteurs industriels comme le textile, où les rejets de teintures doivent être limités au maximum en raison de leur impact visuel important, même à très faibles doses (Robinson *et al.*, 2001).

1.2. Effluent nul et systèmes évapotranspirants

1.2.1 Le concept d'effluent nul

Parmi les solutions de traitement disponibles, certaines ont pour but de réduire à zéro le volume d'eau usée rejetée dans le milieu; on nomme généralement ce type de traitement des systèmes à effluent nul. Les systèmes de traitement à effluent nul (SEN; *zero liquid discharge*) a d'abord été développé pour permettre à différents secteurs industriels de réduire leur consommation d'eau et diminuer leurs coûts de traitement (Koppol *et al.*, 2004). Il permet par ailleurs d'éviter à l'industrie d'avoir à obtenir un permis de rejet pour un effluent potentiellement contaminé. En raison des différentes contraintes du traitement d'eau présentées précédemment, le concept d'effluent nul peut aujourd'hui permettre de répondre à plusieurs problématiques et est donc de plus en plus utilisé (Tong and Elimelech, 2012). À titre d'exemple, les SEN peuvent être utilisés dans les secteurs du textile (Vishnu et al., 2008; Vergili et al., 2012), de la production d'huile de palme (Tabassum et al., 2005) et du raffinage d'hydrocarbures lourds (Heins and Schooley, 2004). Le Tableau 2 résume les principaux motifs et les bénéfices des SEN. La conception d'un SEN peut être plus ou moins complexe dépendamment de la nature de l'eau usée et de l'objectif recherché par l'opérateur du système. La Figure 1 présente une configuration simple d'un tel système et ses principaux produits.

Tableau 1.2 Principaux motifs et bénéfices des systèmes de traitement à effluent nul (*zero liquid discharge;* adapté de Tong and Elimelech, 2012).

Motifs	**Bénéfices**
Normes de rejet plus en plus sévères pour les eaux usées	Respect des normes environnementales (aucun rejet)
Raréfaction des sources d'eau douce	Réutilisation et recyclage de l'eau
Coûts élevés de la disposition des eaux usées	Aucun coût de disposition des eaux usées
Absence de méthode de traitement adéquate	Concentration et isolement des contaminants problématiques
Éveil de la conscience environnementale du public	Protection de l'environnement

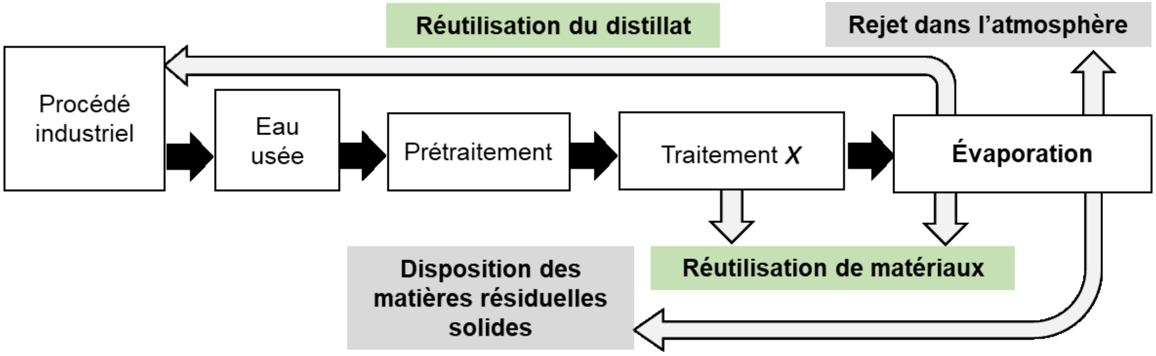

Figure 1.1 Exemple simplifié des étapes de traitement et des produits d'un système de traitement d'eau usée à effluent nul (inspiré de Tong and Elimelech, 2016).

1.2.2 Traitement d’eau par évaporation

L’évaporation, soit la vaporisation des molécules d’eau liquide dans l’air, est utilisée dans certains processus de traitement d’eau usée, incluant les systèmes à effluent nul. Cette étape de traitement peut servir à diminuer la quantité d’eau à traiter et donc à réduire les coûts et ressources nécessaires pour le traitement. Elle permet par la même occasion de concentrer les contaminants ce qui peut dans certains cas faciliter leur traitement ou leur extraction. Dans certains cas, l’évaporation complète d’un effluent permet de recycler les composés en solution dans cet effluent et/ou de récupérer une eau pure par la condensation des molécules d’eau évaporées. Le traitement d’eau par évaporation d’eau s’effectue soit dans des bassins extérieurs exposés à la radiation solaire naturelle, soit dans des évaporateurs spécialement conçus à cet effet. Les bassins ont le désavantage de requérir beaucoup d’espace et l’évaporation y est plutôt lente, alors qu’elle est rapide dans les évaporateurs compacts, mais nécessite alors beaucoup plus d’énergie.

1.2.3 Marais de saules à effluent nul

1.2.3.1 Concept et utilisation

Des systèmes à effluent nul basés sur la phytotechnologie ont vu le jour dans les années 1990. Il s’agit alors de marais de saules utilisés pour le traitement d’eaux usées domestiques au Danemark et conçus de sorte qu’aucune eau ne subsiste à la fin du traitement (Gregersen & Brix, 2001; Brix & Arias, 2005). Cette technologie répondait à un besoin concret des habitants de résidences isolées de traiter leur rejet de phosphore de manière à se conformer aux normes de plus en plus contraignantes. Depuis, l’Irlande envisage d’intégrer cette technologie dans les options permises pour le traitement des eaux usées domestiques de résidences isolées (Curneen & Gill, 2014; Gill *et al.*, 2015) et des études de faisabilité ont été effectués en Mongolie (Khurelbaatar *et al.*, 2017). Le mécanisme préconisé pour réduire le volume de l'effluent est l'évapotranspiration. Ce processus naturel est souvent utilisé en ingénierie environnementale, entre autre précisément pour le traitement de lixiviats contaminés (Białowiec *et al.*, 2011). L'évapotranspiration représente la perte l'eau nette d'un système par évaporation d'une part, et par la transpiration des organismes vivants (*e.g.* des végétaux) d'autre part. Idéalement, les contaminants organiques seront dégradés et les molécules inorganiques problématiques seront transformées dans le substrat du marais par l'action de micro-organismes. Les métaux, métalloïdes et autres contaminants non-dégradables ou récalcitrants seront immobilisés dans le substrat par adsorption, sédimentation ou précipitation. Les contaminants sont ainsi concentrés dans le substrat du marais jusqu'à sa fin de vie utile. Cela permet notamment d'éviter d'avoir recours à d'autres processus de traitement d'eau beaucoup plus couteux et gourmands en énergie et autres ressources, et de gérer des volumes de matière contaminée beaucoup moins important et beaucoup moins fréquemment.

1.2.3.2 Sélection des végétaux

Dans le domaine des phytotechnologies, le saule est fortement exploité et est reconnu entre autres pour sa transpiration importante *(*Hall *et al.*, 1998; Conger & Portier, 2001; Guidi *et al.*, 2008) et sa tolérance à des conditions de croissance défavorables, ce qui en fait un bon candidat pour la réalisation d'un système à effluent nul appliqué au traitement d'eau contaminée. Dans certains cas, particulièrement dans le cas d'effluents fortement concentrés en azote et en phosphore, le saule permet aussi d'assimiler et de valoriser ces «contaminants» grâce à leur croissance rapide et leur forte production de biomasse. La biomasse du saule peut ensuite être valorisée, principalement pour la production d'énergie, ou encore pour la production de produit comme le paillis raméal fragmenté. Toutefois, dépendamment de la localisation du marais et de la composition de l'effluent à traiter, le choix des espèces pourrait varier. De plus, il est important de noter que l'utilisation d'espèces ligneuses telles que le saule peut représenter un défi logistique dans le cas de marais de très grande surface, puisque la biomasse aérienne doit être coupée et récoltée régulièrement (généralement tous les 2 ou 3 ans). Dans tous les cas, certaines caractéristiques devraient être priorisées lors de la sélection des végétaux (Tableau 3).

Tableau 1.3 Principales caractéristiques, ainsi que les bénéfices associés à prioriser lors de la sélection des végétaux qui seront utilisés lors de la conception d'un marais à effluent nul.

Caractéristique	**Bénéfice**
Taux d'évapotranspiration élevé	Réduction de la surface requise pour l'élimination complète de l'effluent
Système racinaire relativement profond	Résilience à de fortes variations du niveau d'eau dans le marais
Adaptation aux milieux humides	Capacité de tolérer des périodes prolongées d'inondation du système racinaire
Système racinaire développé	Maximisation du contact entre la rhizosphère et les contaminants
Tolérance au stress/contamination	Capacité de croître normalement malgré la présence de contaminants ou autre stress (*e.g.* salinité élevée)

1.2.3.3 Défis et enjeux des marais à effluent nul

D'abord il faut distinguer le type d'effluent à traiter, qui influencera la gestion de l'eau dans le système de traitement. Alors que le volume journalier à traiter peut être estimé pour un système de traitement d'eaux usées domestiques, il en est autrement pour un système de traitement de lixiviat qui est entièrement dépendant des précipitations (Kadlec & Wallace, 2008). Ces systèmes de traitement doivent donc permettre de gérer des quantités d'eau importantes, y compris les précipitations hivernales, tout en étant capable de traverser des épisodes plus secs. Dans un climat comme celui du Québec où les précipitations annuelles sont importantes et historiquement à la hausse (1000 mm/an, augmentation de 130 mm/an de 1960 à 2013; MDDELCC, 2017), les quantités d'eau à gérer par un tel système de traitement peuvent s'avérer très importantes (plusieurs milliers de m^3/an). Dans le cas d'effluents de type industriels, les volumes d'eau à traiter sont possiblement plus constants, mais tout de même très élevés. Le taux d'évapotranspiration étant très variable, il est capital de bien connaître ce processus et idéalement de pouvoir faire des prédictions du taux d'évapotranspiration, afin de pouvoir gérer de façon optimale les flux hydriques dans le système, et minimiser les risques de surverses. Finalement, comme les volumes à traiter sont très grands, il est préférable d'optimiser la capacité d'évapotranspiration du système dans son ensemble afin de réduire au maximum la taille de marais de saules requise pour l'atteinte d'un effluent nul. Pour toutes ces raisons, la conception d'un système à effluent nul et le dimensionnement du marais de saules associé peuvent s'avérer particulièrement complexes.

Ensuite, le succès de cette méthode étant lié aux fonctions biologiques des végétaux (*i.e.* évapotranspiration), le système est sujet à différentes contraintes dont la variation saisonnière de l'évapotranspiration, la sensibilité des végétaux eux-mêmes et le destin des contaminants. Une hausse de salinité et une accumulation de contaminants dans le substrat pourraient éventuellement nuire à la croissance des végétaux et il demeure préférable de traiter préalablement l'effluent contaminé afin de réduire au maximum la concentration de polluants. Le traitement primaire d'un affluent contaminé est une étape cruciale de tout système «zéro-rejet» afin de maximiser la période de fonctionnement efficace du système. Dépendamment du type de contamination, il pourra aussi être intéressant d'établir des seuils de phytotoxicité afin de faciliter la gestion du marais de saules. Les saules sont aussi sensibles à diverses pathologies et aux risques de carences que d'autres plantes, ce qui pourrait affecter la performance globale du marais de saules et nécessiter un apport non négligeable en fertilisation. Finalement, dans l'éventualité ou un option de valorisation de la biomasse de saules sera disponible (*e.g.* fabrication de mur anti-bruit, bois raméal fragmenté, etc.) il sera important de s'assurer que les tiges ne contiennent pas de concentrations dangereuses de contaminants.

Quant au destin des contaminants, il est important de mentionner que certains polluants sont susceptibles d'être volatilisés ou encore transloqués dans les parties aériennes des végétaux, entraînant un risque de transfert trophique. Il est donc important d'évaluer ces risques en fonction des contaminants d'intérêt avant d'opter pour cette technologie. La présence de contaminants soulève aussi la question de la durée de vie du système et la planification du retrait et de la disposition périodique des contaminants accumulés dans le substrat. Un des avantages de cette technologie est que plusieurs contaminants très problématiques et sévèrement régulés dans l'eau sont moins problématiques (et donc moins sévèrement normés) lorsqu'il sont associés à un sol. Il est toutefois essentiel de bien caractériser le substrat d'un marais à effluent nul en fin de vie, afin de disposer du substrat de façon adéquate. Par exemple au Québec, la caractérisation et la disposition des sols potentiellement contaminés sont encadrées par le Règlement sur la protection des sols et réhabilitation des terrains contaminés (MELCC, 2019).

Le tableau 1.4 présente un sommaire des différents enjeux et défis associés à l'utilisation de marais à effluent nul. Certaines approche y sont proposées afin d'en prendre compte adéquatement.

Tableau 1.4 Résumé des principaux défis et enjeux liés à l'utilisation de marais à effluent nul pour le traitement d'eau contaminée, ainsi que des approches suggérées pour tenir compte de ces défis/enjeux.

Catégorie	Défis/enjeux	Approche proposée
Gestion de l'eau	Variabilité des volumes à traiter	Conception d'un système hydraulique flexible
	Importance des volume à traiter	Maximisation de l'évapotranspiration pour réduire la surface de marais et le volume de stockage requis
	Variation de l'évapotranspiration	
Gestion des végétaux	Phytotoxicité et durée de vie	Détermination de seuils de phytotoxicité et caractérisation de l'affluent en vue d'estimer l'accumulation dans le substrat
	Fertilisation et lutte aux prédateurs	Suivi fréquent des plantes et traitement si besoin seulement
	Valorisation de la biomasse	Trouver des options de valorisation (après confirmation de la biosécurité de la matière ligneuse)

Destin des contaminants	Possibilité de transfert trophique	Déterminer la capacité de translocation en fonction des contaminants appliqués et utiliser des variétés moins touchées par le broutage
	Possibilité de volatilisation es contaminants	Évaluer la possibilité de volatilisation en fonction des contaminants d'intérêt
	Substrat contaminé en fin de vie utile	Traitement selon les normes en vigueur

1.3. Étude de cas : traitement de lixiviats contaminés aux produits de préservation du bois

1.3.1 Problématique

Les poteaux de service utilisés par les compagnies de télécommunication ou de transport d'électricité sont généralement traités avec différents produits de préservation, comme l'arséniate de cuivre chromaté (ACC) ou le pentachlorophénol (PCP) pour contrer la dégradation du bois par les intempéries, les insectes, les champignons ou les microorganismes. Les précipitations en contact avec les poteaux se retrouvent contaminées par ces produits. Ces lixiviats peuvent donc contenir des métaux comme l'arsenic, le chrome et le cuivre (associé à l'ACC), des composés organochlorés incluant des di-benxo-dioxines/furanes polychlorés (PCDD/Fs), très toxiques et associés au PCP, ainsi qu'une forte demande chimique en oxygène (DCO), dus à libérations d'acides organiques lors de la dégradation du bois comme tel. Les entreprises utilisant des poteaux de bois traités pour leur opération disposent généralement de site d'entreposage où les nouveaux poteaux sont stockés avant d'être acheminés sur leur site d'utilisation, et où les poteaux en fin de vie sont acheminés avant leur disposition finale. Une grande quantité de bois étant ainsi exposés au précipitations, les risques de rejet de contaminants dans l'environnement par lixiviation sont importants. Idéalement, des mesures de collecte et de traitement de ces lixiviats devraient être mises en place pour éviter leur rejet dans l'environnement sous leur forme brute. En 2012, un tel système de collecte et de traitement a été mis en place sous forme de projet pilote sur un site d'entreposage de poteaux destinés au transport d'électricité. Les concentrations moyennes des contaminants mesurées dans ce lixiviat de 2013 à 2017 sont rapportées au Tableau 2.

Tableau 1.2 Valeurs moyennes et maximales, de 2013 à 2017, des concentrations de contaminants mesurées dans les eaux de lixiviation sous un entreposage de poteaux traités à L'ACC et au PCP. Les normes en vigueur dans le secteur pour le rejet de cet effluent dans l'environnement sont présentées à titre informatif.

	Moyenne	**Maximum**	**Norme***
PCDD/F (pg TEQ/L)	185	490	0,0031
As (µg/L)	690	1220	1000
Cr (µg/L)	140	260	1000
Cr(6) (µg/L)	<8,0	11	40
Cu (µg/L)	400	600	1000
PCP (µg/L)	1,3	19	60
DCO (mg/L)	490	940	60

* Norme de rejet des eaux usées de la communauté métropolitaine de Montréal (CMM)

1.3.2 Description du système de traitement

Les poteaux sont entreposés au-dessus d'un bassin étanche (ci-après nommé bassin d'entreposage ou BEP; Figure 2A) de 2240 m^2 et d'une capacité de 543 m^3 servant à récolter les eaux de pluie. L'eau accumulée est éventuellement acheminée dans 4 systèmes de marais filtrants (MF; Figure 2B) conçus et opérés respectivement par les firmes Stantec et HG Environnement, par Polytechnique Montréal et par l'Institut de recherche en biologie végétale (IRBV) de l'Université de Montréal. Les effluents des 4 systèmes de marais sont ensuite combinés et acheminés dans un marais de saules géré par l'IRBV (MS; Figure 2C). Un plan détaillé de la disposition des différents marais et points d'échantillonnage est présenté à l'Annexe 1. Des regards, des piézomètres, des compteurs et plusieurs puits ont été installés dans les marais et à divers points du système hydrique pour permettre de mesurer certains paramètres, d'effectuer des suivis environnementaux et de monitorer l'écoulement des lixiviats dans le système.

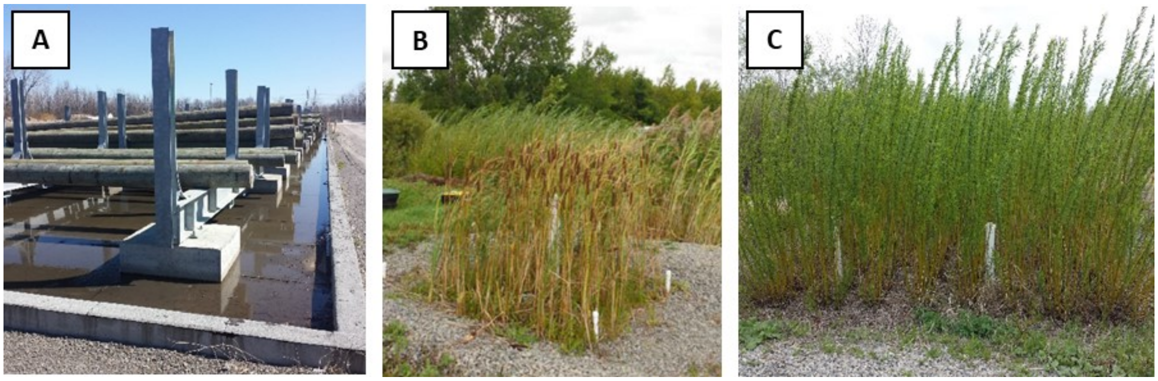

Figure 1.2 A – Espace d'entreposage des poteaux électriques avec le bassin de récupération des eaux de pluie contaminée. B – Un des types de marais filtrants construits pour traiter les lixiviats. C – Marais de saules en début de saison.

Les précipitations accumulées dans le BEP sont dirigées vers un point bas d'où part un système de tuyauterie reliant le BEP au cabanon #1. Une cuve est installée dans le cabanon #2 (voir plan détaillé à l'Annexe 1); lorsque le volume d'eau dans cette cuve descend sous un certain niveau, un système de pompe est actionné dans le cabanon #1 pour acheminer l'eau du BEP vers la cuve. Ensuite, un autre système de pompe est installé dans le cabanon #2 et sert à l'alimentation, à partir de la cuve mentionnée ci-haut, des différents marais filtrants à raison d'un pompage à intervalle d'une heure, jusqu'à un volume déterminé. Cette détermination est faite par l'utilisateur et peut être ajustée ponctuellement au besoin; le volume total envoyé au marais est obtenu en multipliant le temps de fonctionnement des pompes par le débit imposé. Les sorties d'eau des marais et du marais de saules sont gérées par trop-plein, c'est-à-dire que lorsque le niveau d'eau atteint une hauteur déterminée, l'excédent d'eau dans le média est relargué vers le compartiment suivant. Dans le cas des marais, le trop-plein est dirigé vers le marais de saules, et le trop-plein de celui-ci est renvoyé dans le réseau des eaux municipal. Des compteurs cumulatifs installés en amont et en aval du marais de saules permettent de connaître le volume d'eau d'entrée et de sortie.

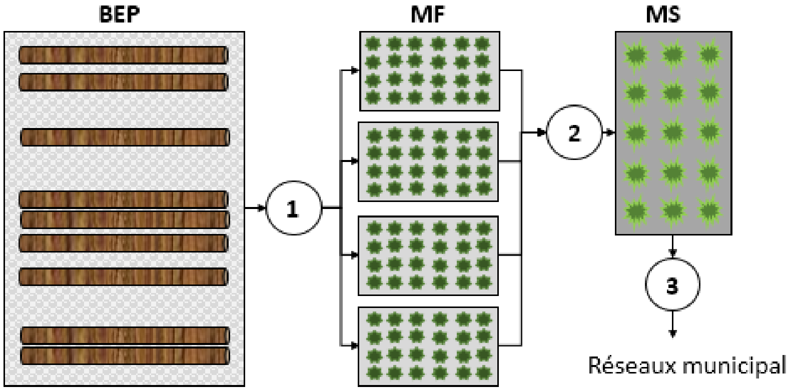

Figure 1.3 Schéma simplifié du système de traitement, avec le bassin d'entreposage des poteaux et du lixiviat contaminé (BEP), la série de marais filtrants (MF) et le marais de saules (MS). 1-3 : points d'échantillonnage de la qualité de l'eau et mesure du débit.

1.3.3 Réalisations antérieures et perspectives

De 2012 à aujourd'hui, ce projet pilote a mené à la rédaction de trois mémoires de maîtrise traitant des méthodes de traitement des lixiviats contaminés aux produits de préservation du bois, d'un article scientifique publié dans la revue Water Science and Technology (Levesque & al., 2017), de plusieurs rapports, énumérés dans le rapport final de Comeau et Brisson (2016) et un total de 14 suivis environnementaux. Tel que rapporté dans le rapport final (Comeau et Brisson 2016), les 4 types de marais et le marais de saules ont permis la réduction de la contamination à l'ACC et au PCP des lixiviats sous les normes gouvernementales. Toutefois, l'effluent des marais et du marais de saules contient des teneurs en manganèse et en dioxines/furanes dépassant les normes. Le mécanisme responsable de la décontamination de l'ACC est la précipitation, avec diverses molécules selon le type de marais. Dans le cas du PCP, il s'agit soit d'une déchloration réductive anaérobie ou d'une oxydation par des microorganismes, selon le marais ici aussi. Finalement, l'optimisation du marais de saules pour en faire un système zéro-rejets a vivement été suggérée comme remédiation à la problématique des dioxines et des furanes, d'où l'élaboration du présent projet de recherche.

1.4 Objectifs de recherche

L'objectif principal de mon projet est d'évaluer la faisabilité de l'utilisation de marais de saules à effluent nul pour le traitement d'eau contaminée. Pour ce faire il sera nécessaire de déterminer la capacité d'évapotranspiration d'un marais de saules et de déterminer l'effet de la contamination sur les saules pour ensuite concevoir et optimiser un système à effluent nul par marais de saules. Je profiterai des acquis de ce projet pour proposer une solution de dimensionnement adaptée à la situation particulière d'Hydro-Québec (décrite dans la section précédente).

1.4.1 Déterminer la capacité d'évapotranspiration de Salix miyabeana (SX67) en marais filtrant

Contrairement aux marais de traitement conventionnels, la conception d'un marais à effluent nul est régie principalement par sa capacité d'évapotranspiration plutôt que sa capacité de traitement. En ce sens, plus notre connaissance de l'évapotranspiration sera grande, plus la conception du marais évapotranspirant sera adaptée et fiable. Pour cela, je veux déterminer le taux d'évapotranspiration d'un des cultivars de saule les plus souvent employé au Québec, *Salix miyabeana* (SX67), puisqu'aucune étude à notre connaissance ne rapporte de résultats pour cette espèce en conditions de marais filtrant. L'hypothèse suivante a été testée :

- **H1.** L'évapotranspiration annuelle de *Salix miyabeana* en marais filtrant par unité de surface dépasse les précipitations annuelles, ce qui rend possible la conception d'un système à effluent nul dans le sud du Québec.

1.4.2 Déterminer la réponse écophysiologique de Salix miyabeana (SX67) à un gradient de concentration de contamination à l'ACC et au PCP

L'objectif général de ce projet étant d'utiliser le saule pour évapotranspirer de l'eau contaminée, l'effet de cette contamination sur les végétaux et leurs fonctions doit être abordé. J'ai testé l'effet d'un gradient de contamination sur l'évapotranspiration et la condition physiologique globale du saule *Salix miyabeana* (SX67). Les contaminants étudiés sont ceux retrouvés dans l'étude de cas d'Hydro-Québec, soit l'ACC et le PCP (incluant les dioxines et furanes). L'utilisation d'un gradient devait par ailleurs nous permettre d'estimer un seuil de tolérance pour notre espèce de saule. Les hypothèses testées ont été les suivantes :

- **H2.** *Salix miyabeana* est une espèce de saules tolérante aux concentrations de contaminants mixtes (ACC et PCP) retrouvées dans le lixiviat brut d'un site de stockage de poteaux traités.

1.4.3 Concevoir et optimiser un système de traitement d'eau à effluent nul par marais de saules

Pour bien évaluer la faisabilité de la technologie et pour proposer des règles de dimensionnement fiables, j'ai choisi de modéliser l'opération complète d'une système de traitement utilisant un marais à effluent nul. Le modèle s'appuie sur les résultats obtenus lors des 2 objectifs précédents et permettra de proposer une solution de dimensionnement concrète dans le cas d'Hydro-Québec. Des scénarios de précipitations sur 20 ans ont été utilisés pour proposer des plans de conception efficace à moyen-long terme. Afin de diminuer au maximum la surface requise par le marais de saules, diverses possibilités d'optimisation de l'évapotranspiration ont été considérées. Cet objectif teste les hypothèses suivantes :

- **H3.** La modélisation hydrologique d'un système de traitement de lixiviat à effluent nul par marais de saules permet de concevoir un système flexible pouvant gérer, sur un horizon de 20 ans, la variation annuelle et intra-annuelle des précipitations et de l'évapotranspiration.

1.5 Organisation de la thèse

La présente thèse est rédigée sous forme d'articles scientifiques rédigés publiés ou en vue d'être publiés dans des journaux scientifiques avec révision par les pairs. Un premier article constituant une revue de littérature sur l'évapotranspiration du saule est présenté au chapitre 2. L'article en question a été publié dans la revue *Journal of environmental management* sous la supervision du professeur titulaire Michel Labrecque et avec la collaboration des 2 directeurs de recherche, Yves Comeau et Jacques Brisson. Un second article traitant de l'évapotranspiration du cultivar de saule *Salix miyabeana* (SX67) est présenté au chapitre 3. L'article a été publié dans la revue *Ecological engineering* avec la collaboration des 2 directeurs de recherche et d'une étudiante au doctorat, Zhanna Grebenschykova. Un troisième article traitant de l'effet d'un gradient de contamination au PCP et à l'ACC et de différents substrats sur le cultivar de saule *Salix miyabeana* (SX67) est présenté au chapitre 4. L'article a été publié dans la revue *Water, soil & air pollution* avec la collaboration des 2 directeurs de recherche, Yves Comeau et Jacques Brisson. Un quatrième article présentant un exercice de modélisation d'un système de traitement à effluent nul par marais de saules est présenté au chapitre 5. L'article est présentement en préparation pour une éventuelle publication dans la revue *Ecological engineering* avec la collaboration des 2 directeurs de recherche. Finalement le chapitre 6 conclue ce document et consiste en une synthèse générale de la thèse présentée, incluant un retour sur les objectifs, les limites des différents chapitres et des marais à effluent nul en général ainsi que les apports des résultats de recherche et les opportunités futures en découlant.

Chapitre 2 | Willows for environmental projects: A literature review of results on evapotranspiration rate and its driving factors across the genus *Salix*

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Status : Published in *Journal of Environmental Management*

Reference : Frédette, C., Labrecque, M., Comeau, Y., & Brisson, J. (2019). Willows for environmental projects: A literature review of results on evapotranspiration rate and its driving factors across the genus *Salix*. *Journal of Environmental Management*, 246, 526-537.

DOI : https://doi.org/10.1016/j.jenvman.2019.06.010

Abstract

Willows are increasingly used for a wide range of environmental projects, including biomass production, leachate treatment, riparian buffers and treatment wetlands. Evapotranspiration (ET), assumed to be high for most willow species used in environmental projects, affects hydrological cycles and is of key interest for project managers working with willows. Here, we present a comprehensive review of ET rates provided in the literature for the genus *Salix.* We aim to summarize current knowledge of willow ET and analyze its variability depending on context. We compiled and analyzed data from 57 studies, covering 16 countries, 19 willow species and dozens of cultivars. We found a mean reported ET rate of 4.6 ± 4.2 mm/d, with minimum and maximum values of 0.7 and 22.7 mm/d respectively. Although results reported here varied significantly between some species, overall interspecific standard deviation (± 3.6 mm/d) was similar to intraspecific variation (± 3.3 mm/d) calculated for *S. viminalis,* suggesting a greater influence of the growing context on ET than species identity. In terms of environmental and management variables, water supply, fertilization and contamination were identified as driving factors of ET across willow species. Effects of root age, experimental context, planting density and soil type were more nuanced. Our findings provide synthetic data regarding willow ET. We encourage practitioners who use ET data from the literature to be aware of the main drivers of ET and to consider the influence of the experimental aspects of a study in order to interpret data accurately and improve project planning.

Keywords: evapotranspiration variability, water use, irrigation planning, wetland design, water loss, willow coppicing

2.1 Introduction

Willows (genus *Salix*) are comprised of hundreds of species, distributed throughout the world, but mostly in the northern hemisphere (Argus, 1986). They can take various growth forms, from small shrubs to large trees. Although some species are adapted to harsh or arid conditions, they more often colonize humid or wet habitats (Dickmann and Kuzovkina, 2014). Aside from traditional pharmaceutical and artisanal uses, willows also have many environmental and energy applications. For some uses, they are produced in short rotation coppice plantations (Zsuffa *et al*., 1984; Gullberg, 1993; Volk *et al*., 2006; Guidi *et al*. 2013), sometimes irrigated with wastewater (Lachapelle-T. *et al*., 2019), sewage sludge (Dimitriou and Rosenqvist, 2011) or leachate (Duggan, 2005). They are thus suitable for use in prevention of leaching of hazardous wastes in evapotranspirative plantations (ET covers; Rüth *et al*., 2007; Mirck and Volk, 2009), phytoremediation of contaminated soils (Witters *et al.,* 2009; Grenier *et al*. 2015), treatment wetlands (Gregersen and Brix, 2001; Curneen and Gill, 2014), and urban and agricultural catchment runoff systems (Hénault-Éthier *et al*. 2017) or even to prevent erosion (Yoder, 1993). Over time, *Salix* species performance has been enhanced by selection and genetic improvement programs (Lindegaard and Barker, 1997; Kopp *et al*., 2001; Smart and Cameron, 2008), and most environmental projects involving willows have used selected or improved cultivars rather than natural species.

Along with high biomass production, willows are known for their high water consumption. Little information is available to enable comparison of willow transpiration (T) with that of other woody species, but it is generally accepted that willow species used for biomass production and other wetland or riparian occurring species in a temperate climate transpire much more than other herbaceous crops (Personn, 1997). Although a high evapotranspiration (ET) rate is essential for some of the uses cited above, such as ET covers, it may be undesirable in other cases. In Europe, for instance, rapid expansion of willow plantations for biomass production has raised concerns about potential disturbance of natural hydrological systems (Dimitriou *et al.,* 2009). An example of such disturbance has been documented in Australia, where willow introduction is thought to have increased water shortage problems, and caused other environmental damage (Doody and Benyon, 2011); willows are now even considered an invasive and prohibited species in some parts of the world (Doody *et al*., 2014; Marttila *et al.,* 2018; Tang *et al.,* 2018). ET is also an important factor to consider for the design and performance evaluation of treatment wetlands (Beebe *et al*., 2014; Białowiec *et al*., 2014), which are sometimes planted with willows. ET rate thus represents an essential design and operational tool for practitioners working with willows, as well as an important factor to consider before extensive introduction of willows in a given area.

ET measurement is complex and requires substantial time, as well as human, technical and financial resources (Allen *et al*., 2011). In most cases, it is far more practical to use values provided by the scientific literature to plan a project involving willows. However, ET rate is highly context-specific, meaning that results obtained in a given set of conditions might not be relevant to practitioners working in a different environment.

Indeed, ET is driven by meteorological conditions, plant related factors and environmental parameters (Allen *et al.,* 1998), all of which can vary greatly from one site/study to another. Meteorological factors can be partially controlled when plants are grown in greenhouses, but are otherwise mainly governed by geographic location. For environmental projects, willows tend to be treated as a single species, but the numerous cultivars derived from many individual species and their respective morphology and physiology are obviously important plant factors that can influence ET variation across the *Salix* genus. Some environmental conditions can be at least partially controlled, such as irrigation, fertilization and coppicing cycle. These factors are most likely to vary depending on the purpose of the study and management decisions, and thus represent a wide range of possible growing conditions. Although not related to the ET process itself, the method used for measurement or estimation of ET is also known to greatly influence results, as most methodological approaches require a high level of expertise and rigor to provide reliable results (see Allen *et al.*, 2011, for a detailed review on that matter). Presentation of methodology and results is also highly heterogeneous, which makes comparing studies difficult. In the end, it can prove rather challenging to find suitable ET information regarding a willow cultivar for a given environmental purpose.

The first objective of this paper was to gather the available ET rate data published for willow species and synthesize this information in a standardized and comparable way. The second objective was to assess the variation of ET across the genus and identify the main drivers of this variability. This review aims to improve our global knowledge of ET potential in rapid growing woody species like willows, and point out opportunities for further research on this topic. Finally, this review should serve as guide for practitioners working with willows for environmental projects to improve irrigation planning, treatment wetland sizing and other decision-making that requires willow ET information.

2.2 Methods

2.2.1 Literature review

Evapotranspiration is, in fact, the combination of both plant T and soil evaporation (E_s). Willows are woody plants that are often fast growing, and thus develop a considerable leaf area. According to Shuttle and Wallace's energy partitioning model (1985), high leaf area index (LAI) implies a reduced Es proportion in ET. This is illustrated in numerous studies presented in this review, as we see the E_s to ET ratio decline in the growing season as the willow leaf cover becomes established (Grip et al., 1989; Iritz et al., 2001; Lindroth et al., 1994; Persson, 1997). For the purpose of this review, T results have been considered along with ET results, under the premise that willow T is a fair estimate of total ET. We are, however, aware that T might represent an under-estimation of the true ET value.

2.2.1.1 Articles selection

A literature review was performed using the keywords "*willow* OR *Salix*" AND "*evapotranspiration* OR *transpiration* OR *water use*", in the Web of Science, Scopus and Google Scholar databases. We selected peer-reviewed articles presenting original results of ET (or T) rates, or data allowing easy calculation of ET rate (*e.g.* irrigation and drainage volumes). We excluded studies presenting data related to ET but not detailed enough to calculate a daily rate (*e.g.* instantaneous rate of T, water-use efficiency), ET results from plant communities including other species than willows and studies measuring willow T at laboratory or growth chamber scale. For instance, for an ET rate provided as an amount of water transpired by a leaf area per unit of time, the leaf area index as well as the typical daily transpiration period (*e.g.* hours of sunlight per day) would have been necessary to convert the results to a mm/d unit. For studies presenting only stemflow results, scaling-up calculations based on sap wood area and various mathematical equations would have been necessary to convert stemflow into transpiration results. ET rates had to be convertible to mm/d units (see section 2.2), and obtained under experimental conditions that could be described by at least 3 of 8 experimental variables selected for results analysis and interpretation, as detailed in section 2.3 (willow species, age of plantation/root system, experimental conditions, water supply, planting density, dominant soil type, fertilization and contamination).

2.2.1.2 ET data transformation

As expected, the ET rates gathered from the literature review varied in absolute value, but also in unit of expression. For comparison purposes, we converted each result to a millimeter per day basis (mm/d), the most common unit for ET rate. For studies that presented total ET values for a given period, we divided these values by the number of days of the experiment. As some authors reported ET rates only graphically, some results were extracted from these graphs. For studies that reported ET rates in terms of volume per plant, the conversion in mm/d was calculated based on the soil area of the plant container (*e.g.* lysimeter surface area) or soil area covered by the plant (inferred from canopy area or planting density).

2.2.2 Comparative analysis based on experimental variables

To interpret the variability of ET rates across studies testing various factors, we used an approach based on a semi-quantitative classification of the experimental and environmental conditions under which the studies were performed. These "conditions", also referred to as "variables" or "factors", include both independent variables and conditions imposed by the authors. We decided to exclude typical meteorological and climatic ET limiting factors such as temperature, solar radiation, wind and water vapor pressure deficit (VPD) of our analysis, since the effect of those factors on potential ET (pET) are already well described in scientific literature related to ET and should mainly be driven by geographic location. We then considered plant related variables and environmental and management variables; each variable was divided into several qualitative or semi-quantitative levels (Table 1).

2.2.2.1. Plant variables

Different plant species have a different T rate according to their intrinsic ecophysiological properties and environment (Bohnert *et al.,* 1995). Including the plant species in a variance analysis would potentially reveal a difference in ET rate between species of the willow genus. T rate should also vary for a given species according to plant growing conditions. To estimate if differences between species were more likely due to taxonomical differences or to growing conditions, we evaluated inter and intraspecific ET rate variation (α_{inter} and α_{intra} respectively). An interspecific variation greater than intraspecific variation would suggest an influence of the species itself on ET rate. ET rate is closely linked to growth rate, which itself is thought to decrease with age (Willebrand and Verwijst, 1993). Consequently, we also considered the age of the plantation as a potential explanatory factor for ET variation. We divided this variable into 3 categories: the establishment year (*first year*), for willows grown from cuttings that have to develop their root system, *young* and *mature* willows (Table 1). Willows with a root system of 5 years of age or more were considered as *mature* because we supposed that, at this point, the root system should be well established.

2.2.2.2. Environmental and management variables

In every study, willows are grown under various conditions determined by the experimenter (management variables) or naturally present on the study site (environmental variables). Some variables like planting density or soil type can be either managed or naturally determined depending on the experimental context. Other factors like water supply can be both determined and random, when plants are provided with rainfall and controlled irrigation at the same time, for instance. Fertilization and contamination are normally deliberately provided to the plants.

The *experimental context* variable was chosen to represent the spatial scale of the willow stand, the *plantation* level being the largest scale and the *mesocosm* the smallest. The levels of this variable also indicate if the experimental unit is an open (*floodplain* and *plantation*) or closed (*treatment wetland* and *mesocosm*) system in terms of hydrological and soil processes.

Water supply is typically considered a limiting factor for ET (Payero *et al*., 2008; Novák, 2012). Not all references provided sufficient methodological information to calculate the actual volume of water provided to the plants. Thus, we classified this variable with semi-quantitative levels (Table 1) according to the global volume of water available or provided to the plants. When water supplies were quantified, we calculated the mean daily volume provided to plants and classified it as follows: < 5 mm/d was considered *low*, 5 to 10 mm/d *medium* and > 10 mm/d *high*. When insufficient quantitative information was provided, water supply was considered *low* when the only water input was rain (in semi-arid to arid climate) or when water stress was imposed or reported by the authors; *medium* when input was rain in humid to very humid climate, when a small amount of artificial irrigation was added to rainfall or when the water table was controlled to a high but non-saturating level; and *high* when high levels of irrigation were provided or when the water level saturated the media (*e.g.* in a treatment wetland or a floodplain).

Planting density can affect willows negatively, by increasing competition between individuals for soil resources, or positively, by maximizing light interception (Willebrand and Verwijst, 1993). We categorized a density of 1 plant per m^2 or less as *low*. The *medium* level included a density from 1 to 4, based on common values used for willow plantation (Willebrand *et al.*, 1993; Volk *et al.*, 2006, Walle *et al.*, 2007). A density higher than 4 plants per m^2 was considered *high*.

We also selected soil type as a variable because of its influence on soil water potential and water availability (Novák, 2012). The relation between water and soil depends on the type of soil particles and can act on two levels. The first level, which is referred to in agriculture as field capacity, determine the soil water content after gravitational drainage has occurred. The more sand is contained in the soil, the less water will remain in the soil at field capacity because of the low attraction between sand particles and water molecules, while an increase in clay proportion, and furthermore in organic content, increases soil water retention capacity (Waller and Yitayew, 2015). However on a second level, at the same water content, water will be more easily available to plants in a sandy soil, were water potential is higher (due lower water molecules attraction) than in a clayey or organic soil water that have lower water potential due to the matrix attraction (Waller and Yitayew, 2015). Because the substrates used in the studies reviewed were never composed of one type of particles alone, we classified this variable according to the dominant type of particles in the media (Table 1). We also treated gravel media separately and excluded articles with a very specific soil type (to avoid having a level of the category with only one observation) or that did not provide information on the media.

The effect of fertilization and contamination were treated for their direct effect on plant T (Feldhake *et al*., 1983; Trapp *et al*., 2000). They were treated as a binomial variable (presence or absence; Table 1) because of the disparities between the type of nutrient sources and contaminants and their method of addition. Landfill leachate was a particular case, and was considered here as both a source of nutrients and contamination. Indeed, willow can use ammonia (typically present in leachate) as a source of a nutrient which can become a toxicant when its concentration is too high. Other leachate constituents such as chlorinated compounds can have a similar toxic effect.

2.2.3 Statistical analysis

When a study tested more than one level of at least one variable, it was considered to have more than one result (n) in the variance analysis. For example, a study measuring ET of two species with two different fertilization levels accounted for four individual results (n=4) in the analysis. When results were reported for many replicates of the same treatment, only the mean value was considered. Using this approach, we built a data base by associating each individual ET rate result to the appropriate level of each variable from Table 1. We then proceeded to the comparative analysis, which consisted of a variance analysis (ANOVA) using R statistical software (version 3.5.1). The model tested in the analysis included all variables, in order to consider their simultaneous effect on ET rate. The ET results followed a Fisher distribution, and a log transformation was used to normalize the data prior to statistical analysis. Missing information for some variables (no observation for one or more variables for a given ET result) yielded an unbalanced statistical plan. However, the most commonly used type of ANOVA (type I) has the effect of giving significantly different results depending on how the variables are ordered in the model when provided with an unbalanced data set. Therefore, we decided to perform a type II ANOVA, which typically gives higher *P* values (less significant results) but is not influenced by the order of the variables in the model. Type II ANOVAs are generally suggested as the best substitute for a type I analysis for unbalanced data (Langsrud, 2003). We also used a correlogram to illustrate possible interactions between the variables of the comparative analysis, except for the variable *plant species*, which is composed of more than fifteen levels. Following the comparative analysis, we also performed linear regression analysis between ET results and both planting density (plants/m^2) and water input (mm/d) for the articles where quantitative information was provided for those two variables. For all analyses, a *P* value lower than 0.05 was considered significant. Finally, α_{intra} was calculated as the standard deviation of the results associated with the most frequently studied species (*S. viminalis*, n=53), while α_{inter} was calculated as the standard deviation between the average ET rate reported for each specie (n=18).

2.3 Results

2.3.1 Article selection and data transformation

Out of the 800+ articles analyzed, 57 met our selection criteria. The studies covered the period from 1986 to 2019 and were from 16 countries, although half (27) originated from Northern Europe. Results were obtained for natural willow species (21 articles) and cultivars (36 articles), each articles testing one to four species and up to 6 different cultivars, for a total of 19 species studied (Table 2). Plants growing conditions ranged from wild to cultivated/controlled, stressed to non-stressed. Overall, 20 studies reported results in mm/d, 26 studies were in mm for a given period (most of the time, per season), and the remaining 9 studies required additional calculations to express results in mm/d. Sixteen articles presented plant T results only.

At least 4 of the 8 variables considered for categorization of the results were provided in each article (Table 2). Information regarding planting density was missing in 6 articles, and root system age in six other articles, while both types of information were missing in 13 studies. However, this information was mainly missing from studies conducted on natural willow stands, where age and density are heterogeneous and more difficult to document. The soil type turned out to be very difficult to categorize due to the wide range of substrates used and the ambiguous nature of the dividing line between clayish and sandy soil (*e.g.* a soil with 50% sand particles and 40% clay particles was considered as *sand* even if it varies greatly from pure sand). After extracting information from all the studies according to the different levels of the categorical variables (see Section 2.2 and Table 1), 110 ET rate results could be treated individually (n = 110, Table 2). Thirty-five articles presented results obtained with homogenous experimental variables (1 study =

1 result), and the studies that tested the most factors resulted in nine individual results (Table 2; Martin and Stephens, 2006). Some studies tested different treatments but were still considered as one result in our analysis because variation between the treatments could not be captured with our variable categorization (*e.g.* 3 irrigation rates tested, but all below 5mm/d, which is considered *low* for the variable *water supply*)

2.3.2 Comparative analysis

According to the 110 observations, ET rates ranged from 0.7 up to more than 20 mm/d. The lowest rate was reported for T (rather than ET), expressed on an annual basis, of *S. fragilis* grown in a gravelly/sandy soil on the banks of a stream (Marttila *et al.*, 2017), while the highest average rate of 22.7 mm/d measured over one growing season by water balance for the species *S. miyabeana* 'SX67' with a mature root system and grown in a treatment wetland with high water supply, medium planting density, organic soil and low contamination and fertilization (Frédette *et al.*, 2019). Mean reported ET rate across all studies was 4.6 mm/d (± 4.5), with about 80% of reported ET rates ranging from 0 to 10 mm/d. We observed some trends regarding factors interactions (Figure 1). For example, we observe that willows growing in *floodplain* are almost systematically associated with *mature* trees, *medium* to *high* water supply, *high* planting density and natural conditions (no fertilization or contamination), that *first year* cuttings and *young* willows are mainly used in *mesocosms* studies while most *mature* trees studied are in *plantation*, or that fertilization was more frequently associated with *treatment wetlands* and *mesocosms* rather than *floodplains* or *plantations*.

2.3.2.1 Plant variables

While 30 and 40 results were reported for *first year* and *young* willows respectively, only 13 pertained to willows with a *mature* root system (Figure 2). The age of the root system did not significantly affect the results, even though fresh stems newly developed from cuttings tended to be associated with slightly lower ET than *young* or *mature* willow plants (4.2 mm/d compared to 5.3 and 5.0 mm/d respectively; Figure 2). Sixteen of the 19 species were associated to 5 results or less, compared to the most studied species, *S. viminalis*, which was associated to 53 results. Three articles did not provide the exact taxonomic identity of the willow studied (*Salix* sp.). There was a significant difference of the results according to species (Figure 2). However, α_{intra} for *S. viminalis* (3.3 mm/d) was very similar to variation between species mean ET rate (α_{inter} = 3.2 mm/d). *Salix amygdalina*, *S. exigua* and *S. psammophila* were the three species with the lowest mean ET rate (< 2 mm/d), while *S. babylonica*, *S. cinerea*, *S. goodgingii, S. miyabeana* and *S. nigra* (all cultivars combined) had the highest (> 7 mm/d; Figure 2).

2.3.2.2 Environmental and management variables

The majority of the articles reviewed studied willows growing either in mesocosms or in plantations (Figure 3). The effect of experimental context on ET rates was not significant (Figure 3). Nonetheless, *treatment wetlands* were generally associated with higher results (7.9 mm/d on average), followed by *mesocosms* (5.7 mm/d), *floodplain* (3.6 mm/d) and finally *plantation* results (2.9 mm/d; Figure 3). Water supply was found to be a significant experimental variable (Figure 3), with *low* water supplies associated to the lower results (2.4 mm/d on average), compared to *medium* and *high* water supply (5.0 and 7.0 mm/d, respectively; Figure 3). Almost half of the results were measured or calculated for willows that were poorly supplied with water (n=47; Figure 3). Furthermore, we found a significant linear correlation between daily water input and daily ET rate for open systems (r^2 = 0.7, Figure 4). The planting density did not significantly explain ET rate variations in our factorial analysis (Figure 3). However, average ET rates were the same for *medium* and *high* planting density (5.4 mm/d), but slightly lower at *low* density (3.2 mm/d; Figure 3). Linear regression of ET rate over planting density did not show a clear trend either (Figure 5), but the few results reported at very high planting density suggest the existence of a threshold, after which ET is limited (here estimated to be approximately 5 plants/m^2; Figure 5). Regarding the type of soil in which willows were grown, most results were reported for sandy soils, followed by clayey soils. No significant effect of soil type was found (Figure 3), but the following average ET rate gradient could be observed: in organic soil (6.1 mm/d) > in clayey soil (5.3 mm/d) > in sandy soil (4.9 mm/d) > in gravel (1.6 mm/d). We should mention that only 3 results were reported for gravel substrate. Finally, fertilization and contamination both had a significant effect in the comparative analysis (Figure 3). Studies that used some kind of fertilization treatment reported ET rates 40% higher on average compared to unfertilized willows (6.1 mm/d vs. 3.5 mm/d). On the contrary, ET rates were generally lower in the presence of contaminants, although average rates were very similar (4.6 mm/d in the presence of contamination compared to 4.7 mm/d in non-contaminated conditions; Figure 3).

2.4 Discussion

Our review shows that mean ET rates in willows are generally below 10 mm/d, but may rise well over that value, reaching up to 23 mm/d. According to a factorial analysis performed on 110 ET rate results from 57 articles, we found that water supply, fertilization and contamination significantly affected ET rates. We identified a strong correlation between daily water input and ET rate in open systems. The effects of plant age, experimental context, and planting density were not statistically significant, although some trends could be observed. Soil type in fact was less important than the other variables, when their simultaneous effect on ET was tested. Willow species seemed to significantly affect ET rates, but α_{inter} and α_{intra} variation of ET were equivalent.

Variation of T rate between species is to be expected, because its regulation mechanisms are not the same for every taxa (Sperry, 2000). These mechanisms are generally adapted to the plant environment (Bohnert *et al*., 1995), a good example being xerophytic species, which display various ways of preventing water loss through T (Fahn and Cutler, 1992). This could explain why *S. psammophila*, a willow species adapted to dry environments (Xiao *et al.*, 2005), had one of the lowest ET rates, while *S. nigra*, a water dependent species (Pezeshki *et al*., 2007), had the highest. Overall, different willow species had different ET rate ranges, but in the end there were so few studies on each species and so many other factors that varied between studies that we cannot conclude that taxonomical identity dictates mean ET rate in the willow genus. Furthermore, the fact that ET variation between willows of the same species (*S. viminalis*) was the same as that between different species suggests that species identity is not the most important factor in ET variation across the willow genus, particularly for species adapted to similar environments (*e.g.* wet habitat). However, willow cultivars developed in breeding programs can promote high T rates for environmental applications like phytoremediation (Smart *et al*., 2005) or promote increased water use efficiency (WUE) and tolerance to water limitation for biomass production (Karp *et al*., 2011). This could explain the high variability of ET in the *S. viminalis* species, which in this review is comprised of more than 20 genetically different cultivars.

Regarding the age of the willow root system, our hypothesis was that plants in their *first year* – the establishment year, as well as *mature* shrubs, which should have a lower growth rate, would be associated with lower ET rates compared to young, fast-growing plants. Indeed, we observed lower ET for plants newly developed from cuttings, but not for *mature* shrubs. However, it appears that the mean average ET rate for mature trees was driven up mainly by the results of one study (Frédette *et al.* 2019); when those results are set aside, mean ET rate for mature trees drops from 5.9 mm/d to 2.4 mm/d. This difference could be explained by the fact that ET results in Frédette *et al*. (2019) were obtained from a treatment wetland with a high water supply, while all the other results from mature shrubs came from plantations with a low water supply. Furthermore, willows in the Frédette *et al.* study were recently coppiced, while most of the other studies were conducted on willows with much older stems. Coppicing of willows is known to help keep the plants in a juvenile, and thus more productive, state and it could then be responsible of those high ET rates. A decrease in biomass production with time has been documented for willows in the past, even in a coppicing system (Willebrand *et al*., 1993), but our analysis did not allow us to demonstrate this pattern. Further studies should be conducted on this specific issue to provide clearer answers.

Our findings suggest that ET rate is greater in closed and relatively small-scale systems (treatment wetlands and mesocosms) than in open and full-size systems (floodplain and plantations). In open systems, ET is higher in floodplains, where the water table (and thus water availability) is generally high and some flooded conditions can even occur, than in plantations, where water may be limited and will drain to lower soil horizons. In comparison, in closed systems like treatment wetlands or some mesocosms, water supply is often equal to or greater than plants' water demand, meaning that water is not a limiting factor and ET occurs at a rate closer to maximal pET. Furthermore, pET can be exceeded in small scale willow stands by processes like an "oasis" or "clothesline" effect (Allen *et al*., 1998; Frédette *et al*., 2019; Dotro *et al*., 2017). An oasis effect is the result of a difference in temperature between willows and their surroundings, due to the cooling effect of ET, which increases available energy to willows by a heat advection effect (Hao *et al*., 2016; Dotro *et al*., 2017). The clothesline effect increases ET on the edges of the willow stand because of enhanced wind influence, as a result of the height difference between willows and the surrounding vegetation (Brix and Arias, 2011; Dotro *et al*., 2017). Both those effects could partially explain higher ET rates reported in mesocosms and treatment wetlands. Another aspect of the experimental context variable is that it shared many associations with other variable levels (Figure 1). Thus, mesocosms were mainly associated with younger willows and medium to high planting density; treatment wetlands generally had a high water supply, medium to low planting density and organic soil; floodplains had a medium to high water supply, high planting density, sandy or clayish soil, unfertilized and uncontaminated environment; and finally, plantations were associated with low to medium water supply, medium planting density, various soil types, but mainly uncontaminated conditions. When considered as the only explanatory variable, experimental context significantly explains ET variation ($p<0.001$). On the one hand, the experimental context might provide a global indicator of ET rate combining many environmental and management variables, but on the other hand, it might be interesting to replace it by finer variables (*e.g.* experimental unit area and permeability) to add precision to a global analysis.

Of all the chosen variables, water supply was one of the most significant driving factors of ET rate variation. Along with meteorological conditions, water is a direct limiting factor for ET, and the impact of water stress on ET rates is generally well described in the ET literature (Sperry, 2000; Bohnert *et al.*, 1995). This review highlights a strong correlation between water supply and ET rate across the willow genus. For open systems where water supplies could be quantified, this factor alone could explain most of the ET rate variation. However, according to the same correlation analysis, the difference between water supply and ET rate increased with increasing water supply, illustrating that the less water is limiting, the more other factors become limiting. This relation may not hold in a closed system, as a lesser effect of water availability on ET has been demonstrated in closed versus open systems (Rana and Katerji, 2000). For example, Guidi and Labrecque (2010) found no increase in ET rate for *S. viminalis* '5027' with very high irrigation rates, compared to "normal" irrigation, in a pot experiment. As previously discussed, water use strategy may also vary from one species to another, depending on its natural environment but also on its breeding strategy. Most of the species studied here are naturally associated with humid habitats, and therefore do not require a very efficient water regulation mechanism, which has given willows their "water-wasting" plant reputation.

Generally, increasing planting density of a crop will also increase biomass yield, until an optimal threshold density is reached; beyond that threshold, a higher density will not produce more biomass due to competition for resources such as for water or light (Assefa *et al*., 2018; Ngouajio, 2001; Willebrand and Verwijst, 1993). As willow biomass is thought to be closely linked to ET (Martin and Stephens, 2006; Marmiroli *et al*., 2012; Białowiec *et al*., 2007), the same threshold hypothesis could apply to ET rate. Our results strongly suggest that the planting density at which willow ET is maximal is higher than 1 plant/m^2 studies using this density systematically reported lower ET rates. No significant differences were found between *medium* and *high* planting density, but plotting ET rates with the corresponding density suggests a threshold around 5 trees/m^2. However, only 12 of the 57 articles reviewed reported results for densities higher than this potential threshold. Furthermore, yield increases for willow have been documented at a density as high as 11 plants/m^2 (Bullard *et al*., 2002).

In addition to water supply, water availability (often expressed as soil water potential) can affect ET, and the type of soil impacts water potential for a given water supply (Rawls *et al*., 1982). However, the soil effect, through attraction force between soil particles and water, can act on two levels, as described in section 2.3.2 of the present manuscript. This dual effect may explain why we did not observe significantly different ET rates according to soil type in this review. Presence of organic matter in the soil even adds another level of interaction by providing additional nutrients to plants, which can increase growth and, consequently, ET rate, which is supported by the slightly higher ET rates reported here for *organic* soils. For the three studies in which *gravel* was used as a substrate, a high ET rate would have been expected, because the substrate was constantly kept saturated with water that should be highly available because of gravel's physical properties. However, low ET rates were measured, probably due to late season measurements in one case (Jing *et al.* 2010), water contamination in another (Białowiec *et al*., 2003) and ET rates reported on an annual basis (including low ET rates in winter) in the last (Marttila *et al*., 2017). This and the previous explanations highlight the simultaneous effect of multiple factors and suggest that soil type alone is not a strong explanatory variable for ET variation.

As expected, fertilization increased willow ET, probably by increasing growth rate. Only one study used fertilization as the main treatment variation, and it reported a 96% increase in ET due to fertilization (Guidi *et al*., 2008). Pistocchi *et al.* (2009) also reported a 51% increase of willow ET when switching from low to high fertilization. For some studies, the variation in the fertilization treatment was due to amendments to the substrate in various forms, such as compost, mechanical-biological pretreated waste material, sewage sludge or other forms of organic matter addition (Rüth *et al*., 2007; Białowiec *et al*., 2007; Martin and Stephens, 2006). Despite the presence of other interacting factors, the *fertilized* treatment in these studies was always associated with slightly higher ET rates. Interestingly, most of the articles that were associated with fertilization were, in fact, exposing willows to various types of wastewater, mainly landfill leachate or from domestic and agricultural source. These types of water did contain nutrients such as nitrogen and phosphorus, but also contained harmful compounds such as chloride and sulfate, high ammonium and salt concentrations, and metalloids, particularly when leachates were the source of fertilization. A good illustration of the dual effect of this type of effluent is provided by Białowiec *et al.* (2003), describing how a low concentration of landfill leachate had a positive effect on willow ET but increasing concentrations became deleterious to the plants. Conversely, Curneen and Gill (2014) reported an increase in ET when using primary (more concentrated) instead of secondary (less concentrated) effluent from domestic wastewater, probably because the beneficial effect of the high levels of nitrogen and phosphorus in this type of wastewater exceeded other potentially negative water characteristics. This may also explain why average ET rate was similar for contaminated and uncontaminated results; 9 of the 14 studies that measured ET rates in contaminated conditions provided fertilized conditions at the same time. When testing chloride contamination only, Stephens (2000) clearly demonstrated the negative impact of increasing chloride concentration on ET. Furthermore, ET rate is frequently used as a toxicity indicator in lab tests, due to its sensitivity to increasing pollutant concentration (Trapp *et al.*, 2000, Clausen *et al.*, 2018). Therefore, contamination and fertilization should be considered together to accurately judge their influence on ET in view of their compensatory effect on each other.

ET is a complex process, and despite the numerous factors evaluated here, there are additional variables that were not analyzed numerically but that could provide a better understanding of ET results. As previously mentioned, biogeographical variation along with meteorological conditions are important factors, and a synthetic and theoretical explanation of those variables can be found in ET literature (see for example Holdridge, 1947 and Allen *et al.*, 1998). For example, higher temperatures and smaller seasonal variations correlate with high ET rates reported in regions as such as Arizona (Nagler *et al.*, 2003) and Louisiana (Conger and Portier, 2001). In this review, we also found that some results reflected coupling and decoupling of willow T with atmosphere and its associated water vapor pressure deficit, which is variable along with plant development (Mirck and Volk, 2009). Otherwise, ET rates show obvious seasonal variation that is accentuated in northern countries, which have shorter growing periods and little to no ET during winter. ET also varies according to phenology and leaf development during the growing period. Although this concept might seem obvious, we consider it pertinent for practitioners planning a project based only on published ET values. According to most of the articles reviewed here, maximum leaf area of willows is generally reached in late summer months, and ET rate is maximal from July to September in the northern hemisphere. This phenological pattern is quite different from that in typical grass species, which develop their total aerial biomass earlier in the season (Persson, 1997). Therefore, the willow crop coefficient (K_c; *i.e.* ratio between willow ET and a reference well-watered grass surface ET) has proven to be very high late in the season (Curneen and Gill, 2016; Persson, 1995; Irmak *et al.*, 2013; Guidi *et al.*, 2008). The crop coefficient is a thus a very useful tool for irrigation planning or project design, and being aware of the temporal variation of willow K_c is an asset.

Finally, although the methodological approach adopted by researchers to measure ET has no direct influence on ET processes, it can contribute to greater ET measurements and calculations. Allen *et al.* (2011) suggested an error range from 5 to 200% in ET measurement, depending on the method used, experimenter experience and training, as well as equipment reliability. Water balance, when performed in a closed system where water fluxes are controlled (*e.g.* lysimeter, treatment wetlands) should yield the most reliable results; this type of method was the most commonly used among the articles reviewed here. When used alone, open water balance can be imprecise due to a high degree of uncertainty regarding leakage and runoff processes. Sap flow approaches are a subset of methods that estimate plant T based on water transport in stems. The method itself presents a number of potential sources of error (Allen *et al*., 2011), and requires extensive calculations and precautions to scale up the ET values from stems to a whole tree stand (Green *et al*., 2003; Grime and Sinclair, 1999). It can therefore be considered a difficult method that requires great expertise and experimental rigor (Allen *et al.*, 2011). Still, the general homogeneity of sapwood in fast-growing willow shrubs developed for coppice plantations makes scaling up results for them easier and more reliable than for other shrubs or trees with more complex arborescence patterns. Modelling methods comprise several distinct approaches, including micrometeorological methods such as energy balance or Penman methods, and models based on different variables like leaf or soil parameters, or a combination of modelling approaches. In this review, we found that studies based on modelling approaches tended to provide low ET rates and less variation across studies than the two previous approaches. This could be due to the fact that most of these modelling studies were conducted in plantations (associated here with lower ET rates) or to over parameterization of models that tend to limit ET in additive or even multiplicative ways. Still, modelling studies are often based on field measurements and serve as practical and sometimes more realistic tools for irrigation planning.

2.5 Conclusions

Overall, willow ET rates reported in scientific literature varied mainly according to plant species, water supply, fertilization and contamination, although species influence remains unclear. It can be hypothesized that environmental/experimental factors have more influence on ET of willows that share similar plant life-forms (*e.g.* fast-growing shrubs naturally found in wet habitats) than taxonomical identity. Water supply seems to be the most limiting factor among those investigated here. In open systems and until pET is reached, there is a positive linear relation between water supply and ET rate. The projected use of the willows (*e.g.* ET cover, treatment wetland, biomass production) informs us on many aspects of the growing conditions, such as the relative water availability and the scale of the willow stand. This variable alone could thus be used to estimate whether ET should be expected to be high or low, although it does not allow precise estimation of ET. A planting density of two to five trees per square meter should be favored to maximize ET and avoid excessive competition. Based on the present review, the effect of soil type on ET remains unclear but may not be one of the most important driving factors. Fertilization and contamination levels provided to plants should be compared to estimate their global effect on plant growth and ET, particularly in cases where willows are irrigated with wastewater or leachate. Finally, biogeographic location will always influence potential ET rate and should be considered by project planners, in addition to the plants, environmental and experimental issues pointed out in this review. Future research on willow ET should focus on 1) specifying the root or stem age effect on ET, 2) confirming the optimal density for ET processes, as well as 3) testing whether, under a given set of growing conditions, species or cultivar identity has a significant effect on ET or not.

Acknowledgments

This work was supported by the Phytotechnology NSERC/Hydro-Québec Industrial Research Chair.

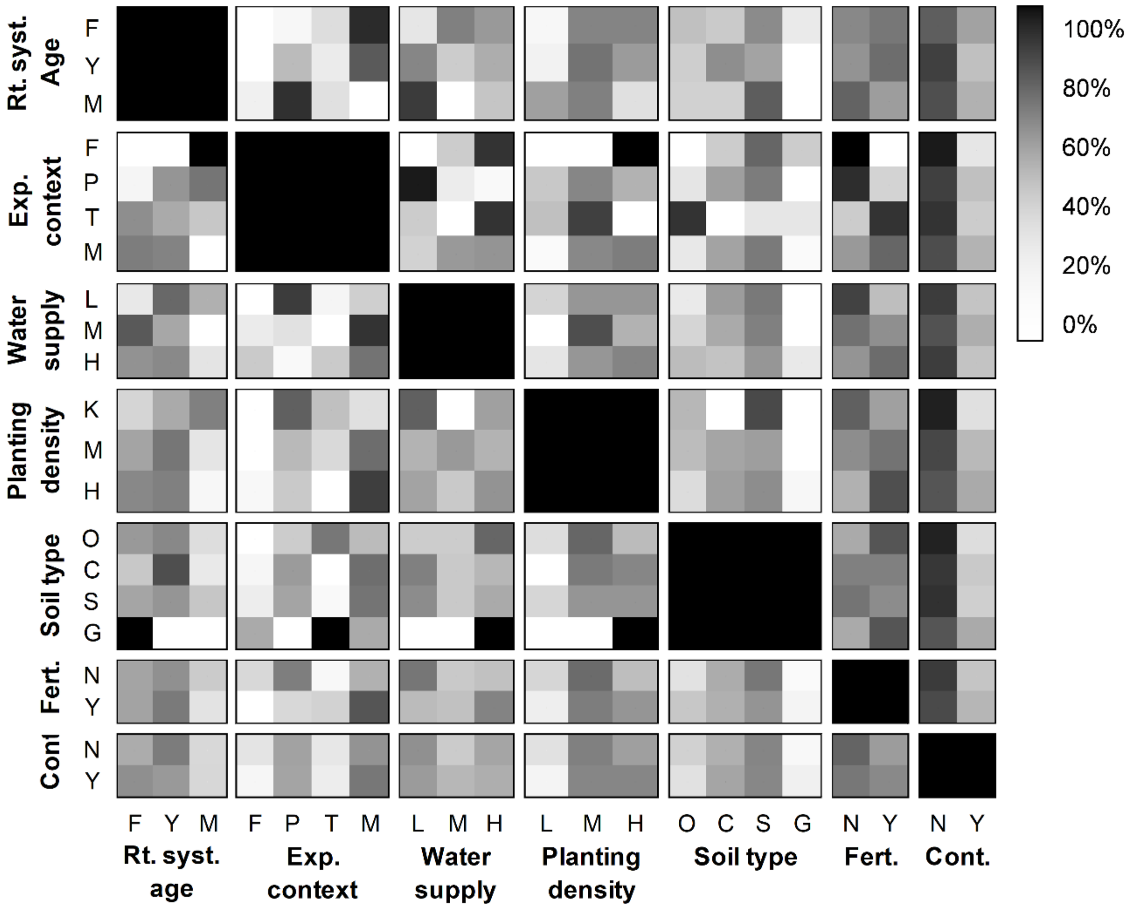

Figure 2.1 Correlogram illustrating the frequency (%) of association between the levels of nine variables selected to explain the variation of evapotranspiration rates across the willow genus (*Salix* sp.). Darker colours indicate a frequent association between levels of two variables (black = 100%, *i.e.* levels always associated), while pale colours indicate that the levels of the two variables were not likely to be combined (white = 0%, *i.e.* levels never associated). The codes used for variable levels are detailed in table 1 of the present article.

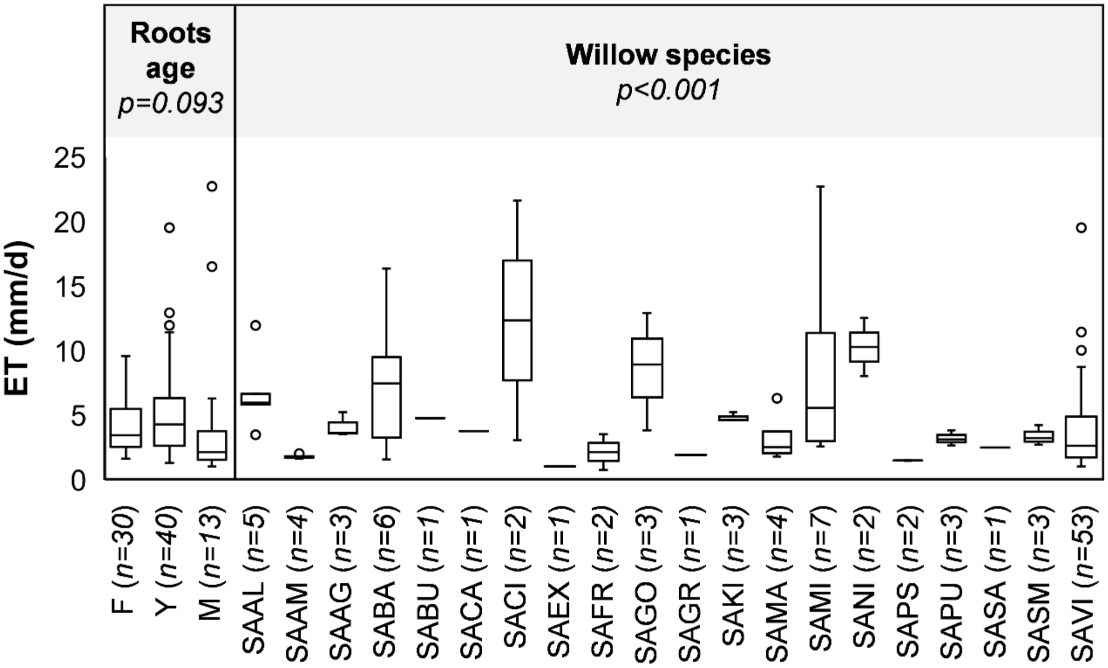

Figure 2.2 Mean evapotranspiration (ET) rates reported in 57 articles in 16 countries, according to plant related variables (root system age and species). Numbers in parentheses (n) represent the number of average results considered for each variable level. The codes used for variable levels are detailed in table 1 of the present article. P values indicate if the variables affect significantly (α=0.05) ET results according to a Type II ANOVA analysis testing the simultaneous effect of 10 variables.

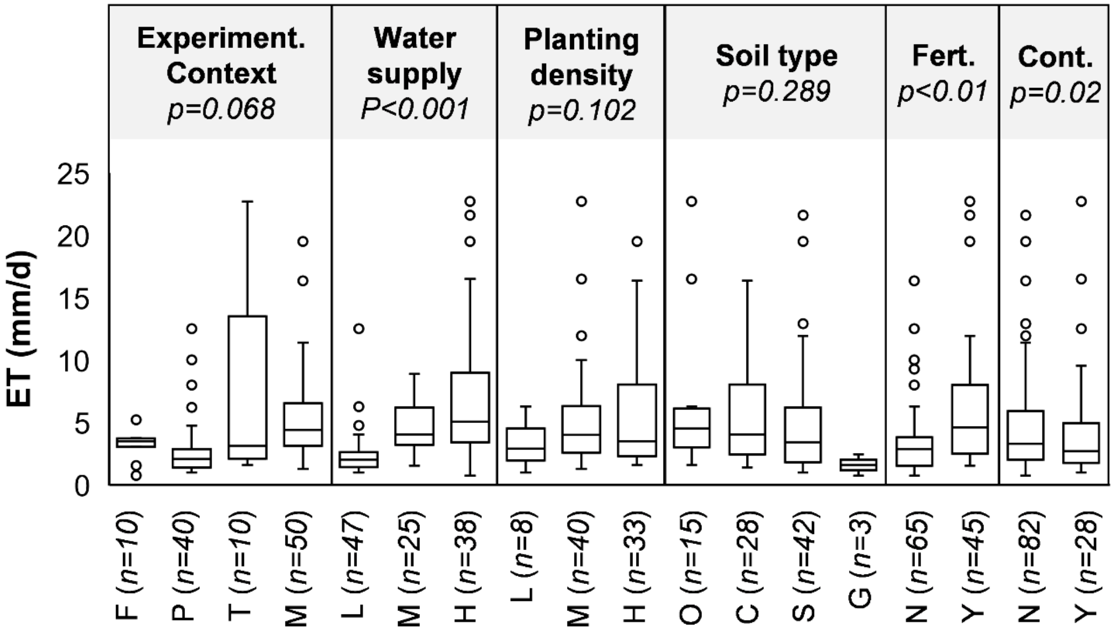

Figure 2.3 Mean evapotranspiration (ET) rates reported in 57 articles in 16 countries, according to experimental/management variables (experimental context, water supply, planting density, dominant soil type, fertilization and contamination). Numbers in parentheses (n) represent the number of average results considered for each variable level. The codes used for variable levels are detailed in table 1 of the present article. P values indicate if the variables affect significantly (α=0.05) ET results according to a Type II ANOVA analysis testing the simultaneous effect of 10 variables.

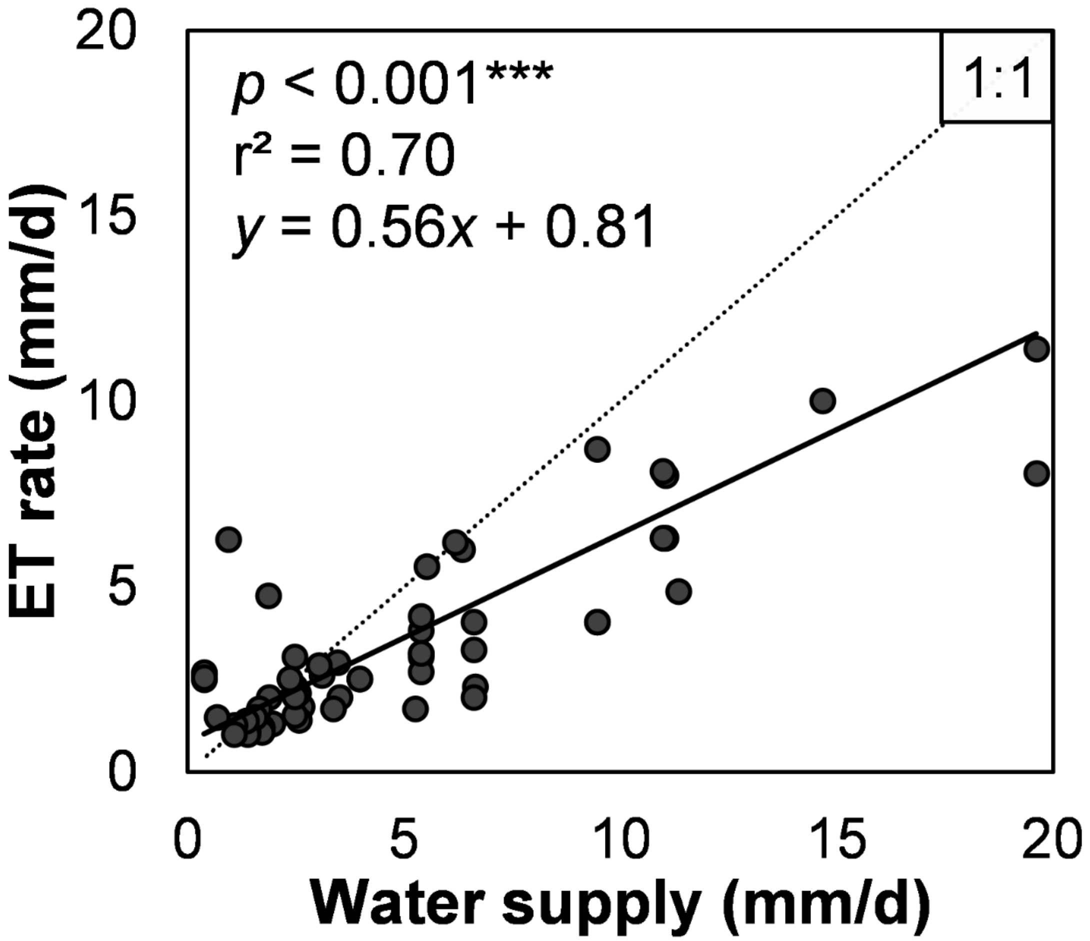

Figure 2.4 Summary of the linear regression between mean daily evapotranspiration rate of willows reported in scientific literature and the amount of water supplied daily, either by precipitation or irrigation (*n = 63*). Reference articles included in this analysis are detailed in Table 2 of the present article, and are comprised of studies of open systems with water table low enough to allow drainage.

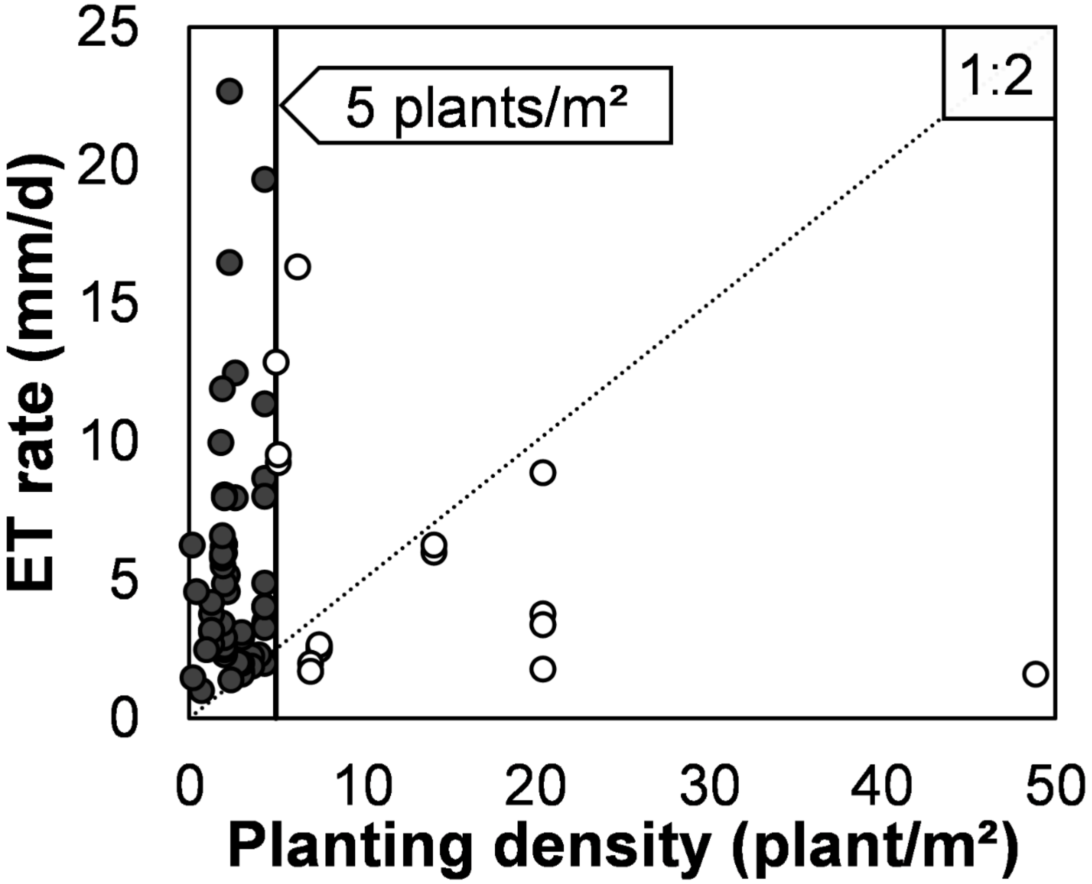

Figure 2.5 Mean daily evapotranspiration rate of willows reported in scientific literature in relation to planting density (*n* = *75*). Reference articles included in this analysis are detailed in Table 2 of the present article. An arbitrary threshold (dashed line) for ET was drawn at a planting density of 5 trees per m^2.

Table 2.1 Summary of ten variables selected to categorize, compare and identify driving factors of willow (*Salix* sp.) evapotranspiration rates results found in the scientific literature.

Type	Variable	Levels	Description	Code
Plant variables	Willow species	19 species (see Table 2 for species listing and codes)		
	Age of plantation	First year	Establishment year	F
		Young	2 to 5 years old roots	Y
		Mature	> 5 years old roots	M
Environmental/management variables	Experimental context	Flood plain	Natural stands in wet habitat	F
		Plantation	Mand made plantation or natural stand in mesic to dry habitat	P
		Treatment wetland	Pilot and full-scale	T
		Mesocosm	Lysimeters and pots	M
	Water supply	Low	> 10 mm/d or saturated root zone	L
		Medium	5 to 10 mm/d or field capacity	M
		High	< 5mm/d or water deficit	H
	Planting density	Low	≤ 1 plants/m^2	L
		Medium	1 to 4 plants/m^2	M
		High	> 4 plants/m^2	H
	Dominant soil type	Organic	Significant organic matter content	O
		Clay	> 50% clay particles	C
		Sand	> 50% sand particles	S
		Gravel	> 50% gravel content	G

Fertilization	Yes	Fertilizer, soil amendment or nutrient rich wastewaters	Y
	No		N
Contamination	Yes	Soil or water contamination	Y
	No		N

Table 2.2 Range of evapotranspiration rates (mm/d) reported in 57 articles for 19 different willow species (and various cultivars) in 16 countries, along with the corresponding information about plants, experimental and methodological variables. Results of transpiration only are indicated in parentheses (T). Information missing about some variables is due either to non-reported information or to values that did not fit the selected levels of a variable. Numerical values of water supply and planting density are detailed in parentheses when available. The codes used for variable levels are detailed in table 1 of the present article. Each article tested one to nine experimental treatments (n), for a total of 110 mean results considered for comparative analysis.

Species **'cultivar'**	**Code**	**ET range** **(mm/d)**	**Age**	**Context**	**Water** **(mm/d)**	**Density** **(plant/m^2)**	**Soil**	**Fert.**	**Cont.**	**n**	**Country**	**Ref.**
S. alba 'SI62-059'	SAAL	3.4-11.9	F, Y	M	M	M (1.9)	S	Y, N	N	4	Italy	1
S. alba 'SI62-059'	SAAL	4.6-7.0	Y	M	M	M (1.9)	S	Y	N	1	Italy	2
S. amygdalina	SAAM	0.6-2.3	F	M	H	H (48.8)	G	Y	Y	1	Poland	3
S. amygdalina	SAAM	1.0-3.0	F, Y	M	L, M (3.4-5.3)	H (7)	S	Y	Y	3	Poland	4
S. amygdaloïdes	SAAG	3.6-5.2	-	F	H, M	-	S	N	N	2	U.S.	5
S. amygdaloïdes	SAAG	3.5 (T)	-	F	H	-	S	N	N	1	U.S.	6
S. babylonica	SABA	1.5-6.6	-	F	H, M	-	-	N	N	2	Australia	7
S. babylonica	SABA	2.4	F	T	H	-	G	Y	N	1	China	8

S. babylonica	SABA	9.3-9.6	F	M	H	H (5.1)	C	Y, N	Y,N	2	Canada	9
S. babylonica	SABA	16.4	-	M	H	H (6.25)	C	N	N	1	U.S.	10
S. bujartica 'Germany'	SABU	4.8 (T)	Y	P	L (1.9)	-	C	N	N	1	Sweden	11
S. caroliniana	SACA	3.8	M	F	H	-	-	N	Y	1	U.S.	12
S. cinerea	SACI	21.6	-	T	H	-	S	Y	N	1	Belgium	13
S. cinerea	SACI	3.0	-	F	H	H	C	N	N	1	Czechoslovakia	14
S. exigua	SAEX	0.7-1.6	M	P	L (1.1)	L (0.7)	S	N	N	1	U.S.	15
S. fragilis	SAFR	3.5	-	F	H	-	-	N	N	1	Australia	16
S. fragilis	SAFR	0.7	-	F	H	-	G	N	N	1	New-Zeland	17
S. gooddingii	SAGO	2.5-8.9 (T)	F	M	M	H (20.4)	S	Y	Y, N	2	U.S.	18
S. gooddingii	SAGO	12.9 (T)	Y	M	H	H (5.0)	S	N	N	1	U.S.	19
S. gordejevii	SAGR	1.9 (T)	-	P	L	H (3.6)	S	N	N	1	China	20
S. kinuyanagi 'Kimura'	SAKI	4.6-5.4	F	M	H	M (2.2)	S	Y, N	Y, N	2	New-Zealand	21
S. kinuyanagi 'Kimura'	SAKI	4.6	Y	M	H	L (0.4)	S	Y	Y	1	New-Zealand	22
S. matsudana	SAMA	2.1	M	P	L (2.6)	L	S	N	N	1	China	23

S. matsudana	SAMA	1.8	M	P	L (2.7)	L	S	N	N	1	China	24
S. matsudana	SAMA	6.3	M	P	L (0.9)	L (0.2)	S	N	N	1	China	25
S. matsudana	SAMA	1.2-5.3 (T)	M	P	L (3.0)	-	S	N	N	1	China	26
S. miyabeana ‘SX67’	SAMI	16.5-22.7	M	T	H	M (2.3)	O	Y	Y	2	Canada	27
S. miyabeana ‘SX67’	SAMI	5.5-6.2	F, Y	P	M (5.5-6.2)	M (2.0)	O	N	N	2	Canada	28
S. miyabeana ‘SX64’	SAMI	2.5-2.7 (T)	Y	P	L (0.4)	H (7.5)	-	N	Y	1	U.S.	29
S. miyabeana ‘SX64’	SAMI	2.7-3.9	F	M	M (5.4)	M (1.3)	-	N	Y, N	2	U.S.	30
S. nigra	SANI	6.0-13.0 (T)	Y	P	L, M	M (2.6)	C	N	Y	2	U.S.	31
S. psammophila	SAPS	1.5 (T)	-	P	L (1.6)	-	S	N	N	1	China	32
S. psammophila	SAPS	1.4	-	P	L	L (0.2)	S	N	N	1	China	33
S. purpurea ‘9882-34’	SAPU	3.1-3.8	F	M	M (5.4)	M (1.3)	-	N	Y, N	2	U.S.	30
S. purpurea ‘9882-34’	SAPU	2.6 (T)	Y	P	L (0.4)	H (7.5)	-	N	Y	1	U.S.	29
S. sachalinensis ‘SX61’	SASA	2.5 (T)	Y	P	L (0.4)	H (7.5)	-	N	Y	1	U.S.	29
S. sachalinensis x S. miyabeana ‘9870-40’	SSSM	3.2-4.2	F	M	M (5.4)	M (1.3)	-	N	Y, N	2	U.S.	30
S. sachalinensis x S. miyabeana ‘9870-23’	SSSM	2.7 (T)	Y	P	L (0.4)	H (7.5)	-	N	Y	1	U.S.	29

S. viminalis	SAVI	10.0	-	P	H (14.7)	M (1.79)	S	N	N	1	Switzerland	34
S. viminalis ‘1023’ ‘1047’ ‘1052’ ‘1054’	SAVI	1.4-1.7	-	P	L (1.4-1.7)	-	C, S	N	N	2	Poland	35
S. viminalis ‘Inger’ ‘Sven’ ‘Tordis’ ‘Torhild’	SAVI	1.9-7.6	Y	M	H	H (4.35)	O	Y, N	N	2	Ireland	36
S. viminalis	SAVI	1.5-2.9	F, Y	T	L, H	M (3.0)	O	Y, N	N	4	Ireland	37
S. viminalis ’78-183’	SAVI	6.3-8.3	Y	M	H (11.0)	M (2.0)	C, S	Y	N	2	Sweden	38
S. viminalis ‘Tora’	SAVI	2.2-7.5	F, Y	M	M, H (6.4-11.4)	M (2.0)	C	Y	Y	3	Sweden	39
S. viminalis ‘Tora’	SAVI	2.3-8.3	Y	M	L, H (4.0-11.0)	M (2.0)	C, S	Y	N	4	Sweden	40
S. viminalis ‘Bjorn’ ‘Tora’ ‘Jorr’	SAVI	2.7-5.7	F, Y	T	H	L	O	Y	N	2	Denmark	41
S. viminalis ‘77683’ ‘77666’	SAVI	3.0	Y	M	L	-	S	N	N	1	Sweden	42
S. viminalis ‘SQV 5027’	SAVI	6.0-6.3	F	M	M, H	H (14.1)	O	Y	N	2	Canada	43
S. viminalis	SAVI	2.6	Y	P	L (3.1)	M (2.0)	C	Y	N	1	Sweden	44
S. viminalis ‘L78183’ ‘Loden’ ‘Jorr’ ‘Rapp’ ‘Tora’	SAVI	0.7-2.1 (T)	Y	P	L (2.6)	M (2.4)	C	N	N	1	Sweden	45
S. viminalis	SAVI	2.9-3.0	Y	P	L (3.5)	M (2.0)	C	Y	N	1	Sweden	46
S. viminalis ‘Jorr’	SAVI	2.0-19.5	F, Y	M	L, M, H (6.6-19.6)	H (4.4)	C, S	Y, N	N	9	U.K.	47
S. viminalis ‘77075’ ‘77077’ ‘77082’ ‘77083’ ‘77683’ ‘82007’	SAVI	2.0-3.7	Y, M	P	L (2.5)	M, H (3.0-4.0)	C, S, O	Y	N	5	Sweden	48

S. viminalis	SAVI	1.6-2.3	-	P	L (1.9)	-	C	N	N	1	Sweden	49
S. viminalis ‘Régalis’	SAVI	1.0-1.2	-	P	L (1.4-1.7)	-	S	N	Y, N	6	Germany	50
S. viminalis	SAVI	1.2 (T)	M	P	L (1.0)	-	-	N	Y	1	Belgium	51
S. viminalis ‘Tora’	SAVI	1.3-1.5	Y, M	P	L (0.7-1.1)	M	C, S	N	N	1	Germany	52
S. viminalis ‘Q683’	SAVI	1.8-3.4	1	M	H	H (20.4)	S	N	Y, N	2	U.K.	53
S. viminalis ‘Jorunn’	SAVI	2.5 (T)	-	P	L (2.4)	L (1.0)	-	N	N	1	U.K.	54
Salix sp.	SASP	3.1	-	P	L	-	C	N	N	1	Sweden	55
Salix sp.	SASP	3.1 (T)	-	F	H	-	-	N	N	1	U.S.	56
Salix sp.	SASP	1.1-1.4	-	P	L (2.0)	-	-	N	N	1	Germany	57

1. Guidi *et al*., 2008; 2. Pistocchi *et al*., 2009; 3. Białowiec *et al*., 2003; 4. Białowiec *et al*., 2007; 5. Kabenge *et al*., 2012; 6. Irmak *et al*., 2013; 7. Doody and Benyon, 2011; 8. Jing *et al*., 2010; 9. Cureton *et al*., 1991; 10. Pauliukonis et Schneider, 2001; 11. Hall *et al*., 1998; 12. Duan *et al*., 2017; 13. Kučerová *et al*., 2001; 14. Přibáň and Ondok , 1986; 15. Mata-González *et al*., 2014; 16. Doody *et al*., 2011; 17. Marttila *et al*., 2018; 18. Glenn *et al*., 1998; 19. Nagler *et al*., 2003; 20. Duan *et al*., 2017; 21. Marmiroli *et al*., 2012; 22. Royygard *et al*., 1999; 23. Wang *et al*., 2015; 24. Wang *et al*., 2019; 25. Yin *et al*., 2014; 26. Peng *et al*., 2015; 27. Frédette *et al*., 2018; 28. Guidi Nissim *et al*., 2014; 29. Mirck and Volk, 2009; 30. Mirck and Volk, 2010; 31. Conger and Potier, 2001; 32. Huang *et al*., 2014; 33.Huang *et al*., 2015; 34. Benettin *et al*., 2018; 35. Borek *et al*., 2010; 36. Curneen and Gill, 2014; 37. Curneen and Gill, 2016; 38. Dimitriou *et al*., 2004; 39. Dimitriou *et al*., 2010; 40. Dimitriou *et al*., 2011; 41. Gregersen and Brix, 2001; 42. Grip *et al*., 1989; 43. Guidi and Labrecque, 2010; 44. Iritz *et al*., 2001; 45. Linderson *et al*., 2007; 46. Lindroth *et al*.,

1994; 47. Martin and Stephens, 2006; 48. Persson, 1995; 49. Persson, 1997; 50. Rüth *et al*., 2007; 51. Scheirlink *et al*., 1996; 52. Schmidt-Walter *et al*., 2012; 53. Stephens *et al*., 2000; 54. Tallis *et al*., 2013; 55. Halldin and Lindroth, 1989; 56. Budny and Benscoter, 2016; 57. Hartwich *et al*., 2016.

Chapitre 3 | Evapotranspiration of a willow cultivar (*Salix miyabeana* SX67) grown in a full-scale treatment wetland

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Status : Published in *Ecological Engineering*

Reference : Frédette, C., Grebenshchykova, Z., Comeau, Y., & Brisson, J. (2019). Evapotranspiration of a willow cultivar (*Salix miyabeana* SX67) grown in a full-scale treatment wetland. *Ecological engineering*, 127, 254-262.

DOI : https://doi.org/10.1016/j.ecoleng.2018.11.027

Abstract

Since woody plants like willow are used increasingly in treatment wetlands, there is a growing need to characterize their ecophysiology in these specific growing conditions. For instance, evapotranspiration (ET) can be greatly increased in wetlands, due to factors like high water availability as well as oasis and clothesline effects. Few studies report willow ET rates measured in full-scale constructed wetland conditions, and fewer still in a temperate North-American climate. The objective of this study was to measure and model evapotranspiration of a commonly used willow cultivar, *Salix miyabeana* (SX67), to provide the ET rates and crop coefficient for this species. During two growing seasons, we studied a 48 m^2 horizontal subsurface flow willow wetland located in eastern Canada, irrigated with pretreated wood preservative leachate. Over two seasons, from May to October, we measured a mean monthly evapotranspiration rate of 22.7 mm/day (16.5 mm/d modelled), for a cumulative seasonal ET of 3954 mm (2897 mm modelled) and a mean crop coefficient of 6.4 (4.2 modelled). Both the evapotranspiration results and leaf area index (LAI) were greater than most results reported for open field willow plantations. Maximal stomatal conductance ($\bar{G}_s$) was higher than that expected for deciduous trees and even for wetland plants, and mean values correlated well with temperature, solar radiation, relative humidity and day of the year. We demonstrated that an ET model using $\bar{G}_s$, LAI and water vapor pressure deficit (VPD) as parameters could predict the evapotranspiration rate of our wetland. This simplification of traditional ET models illustrates the absence of evapotranspiration limitations in wetlands. Furthermore, this study also highlights some factors that can enhance ET in treatment wetlands. Our

results should both improve the design of treatment wetlands using willows, and provide a simple ET predictive model based on major evapotranspiration drivers in wetlands.

Keywords: willow crop coefficient, wetland evapotranspiration, stomatal conductance, willow leaf parameters, evapotranspiration modelling, zero-discharge wetlands

3.1 Introduction

Treatment wetlands, or vegetation filters, are now commonly used for treatment of various types of wastewater (Valipour and Ahn, 2017). "Artificial" wetlands are generally planted with herbaceous plants like *Phragmites, Typha*, graminoids or other aquatic and semi-aquatic species (Kadlec and Wallace, 2008). More recently, woody species of the *Salix* genus (willows), generally studied for biomass production, are being tested and used for wastewater treatment purposes. *Salix* species are used in stream restoration projects (Pezeshki *et al.*, 2007). They are mostly hydrophilic, tolerate hypoxic conditions and great water fluctuations well, have a high growth rate and develop a vigorous root system (Kuzovkina *et al.*, 2008), making them good candidates for treatment wetland purposes. Another advantage of using woody plants for water treatment is the added value of biomass production that can be used for bioenergy and biofuel processes (Duggan *et al.*, 2005). Consequently, there is a growing interest in willow for use in treatment of landfill leachate, domestic wastewater or other nitrogen-rich wastewater (Białowiec *et al.*, 2003; Dimitriou and Aronsson, 2011; Guidi *et al.*, 2014). Fast growing willows are also known for their great evapotranspiration (ET), which led to the development of a new specific type of treatment wetlands called “zero-discharge wetlands” (ZDWs; Dotro *et al*., 2017). The design of ZDWs is based mainly on the ET capacity of the plant selected. They operate without liquid effluent, immobilizing and concentrating contaminants in the wetland substrate and preventing any release of residual contamination in the environment. Depending on the type of water contamination, ZDWs can function as the final step of a treatment plant or as a secondary treatment. Such wetlands are now well implanted in Scandinavian countries, mainly in Denmark, where the concept was first developed (Gregersen and Brix, 2001; Brix and Arias, 2011), and Ireland (Curneen and Gill, 2014). Conclusive tests have also been performed in Mongolia, under very cold climatic conditions (Khurelbataar *et al*., 2017), and zero-discharge wetlands are currently being tested in other locations.

Sound scientific knowledge of the ET rate of the species used is an essential tool to design a treatment wetland because of the direct impact it will have on the wetland hydraulics (Kadlec and Wallace, 2008) and its removal performance (Beebe *et al*., 2014; Białowiec *et al*., 2014). It is even more important for zero-discharge wetlands, where ET is the main "treatment" process, ensuring that no liquid waste will flow out of the wetland. While many studies have been published on willow ET, very few concern willows growing in full-scale treatment wetland conditions. However, ET in artificial wetlands can differ greatly from ET measured in a plantation, and can significantly surpass potential ET (Dotro *et al.,* 2017).

The willow species most studied for ET is *Salix viminalis,* its hybrids and their numerous cultivars (Frédette *et al.* 2018). Although widely used in Europe, some long-term studies have pointed out that, in North America, cultivars of *S. viminalis* are more prone to diseases and insect attacks than other cultivars (Labrecque and Teodorescu, 2005; Nissim *et al.*, 2013). Instead, other cultivars from species like *Salix eriocephala, S. purpurea*, *S. nigra* and *S. miyabeana* are frequently used (Smart and Cameron, 2008). In eastern Canada, Nissim *et al*. (2013) concluded that *S. miyabeana* and some indigenous species were more suited for plantations than *S. viminalis*. *Salix miyabeana* has also shown high biomass production (Labrecque and Teodorescu, 2005; Pitre *et al*., 2010), good phytoremediation capacity and high tolerance to various contaminants like petroleum hydrocarbons (Grenier et al., 2015), metals and metalloids (Pitre *et al*., 2003; Purdy and Smart, 2008) and nitrogen-rich wastewater (Nissim et al., 2014). Considering that some cultivars of this species, such as SX67 and SX64, have been proven to be well suited for some regions of North America, there is now interest in using *S. miyabeana* for treatment wetlands (Lévesque *et al.*, 2017, Grebenshchykova *et al*., 2017), ET cover (Mirck and Volk, 2009) and zero-discharge wetlands (Frédette *et al.*, 2017). However, we found a single study that reported ET rates for this species, based on the cultivar SX64 grown on a contaminated site for leachate minimization in the north-eastern United States (Mirck and Volk, 2009). For all species of willow combined, we found four studies reporting ET rates in treatment wetland conditions, most of them conducted in Europe and none in the Americas. There is thus a clear lack of knowledge regarding the ET capacity of economically important North American willow cultivars, like *S. miyabeana*, growing in treatment wetland conditions.

The first objective of our study was to measure the ET rate and provide a crop coefficient (K_{ET}) for *Salix miyabeana* (SX67) grown in treatment wetland conditions in a sub-boreal temperate climate. The second objective was to propose a predictive ET model, based on simple meteorological and leaf parameters, which would be coherent with the wetland growing conditions and physiology of fast growing willow species like *S. miyabeana*. While the first objective would serve as a practical tool for development of a better treatment wetland design and add to our knowledge of the ET of North American willow cultivars, the predictive model would enable the transfer of our results to different climatic scenarios and to other willow species that are physiologically similar but have different leaf and phenological parameters.

3.2 Material and methods

3.2.1 Study site

The wetland studied is located in an industrial part of the city of Laval, Québec, where mean annual precipitation and temperature are 1000 mm and 6.8 °C, respectively, elevation is 91 m above sea level and the growing season is about 170 days. This willow wetland was established in 2012 and serves as a final polishing step connected to a series of other constructed wetlands treating leachate contaminated with utility wood pole preservatives (chromated copper arsenate and pentachlorophenol). The treatment system receives contaminated leachate from an open storage tank situated directly under the stored wood poles, and this, only during the plants' growing season and when there is no risk of water freezing in the system. The rest of the year, the wastewater is stored in the open tank until the next season. More details about the experimental treatment project are provided in Levesque *et al*. (2017). The willow wetland is a horizontal subsurface flow wetland 8 m wide by 6 m long (Figure 1), lined with a waterproof membrane and filled with a mix of black peat (20%) and sand (80%) with a porosity of 50% (determined by measurement of pore volume by liquid imbibition).

Throughout this study, the mean hydraulic loading rate of the willow wetland was 55 L m^{-2} d^{-1} during the operating season, for a mean daily flow of 2.6 m^3. Water flowing into the willow wetlands contained residual contamination from the treatment wetlands upstream, including pentachloro dibenzodioxins/furans (94.5 pg TEQ/L), arsenic (0.12 ppm), chromium (0.01 ppm) and copper (0.02 ppm), and was relatively poor in nutrients (N: 0.12 ppm, P: 0.05 ppm, K: 3.93 ppm). The willows did not display any significant phytotoxic symptoms, but did show signs of nitrogen deficiency.

The wetland was fertilized in 2014, and again at the beginning of 2017, with a slow-acting fertilizer in (Acer 21-7-14). The shoots were cut back at the end of the 2014 season to maintain a juvenile state and high productivity (Nyland, 2016; Abrahamson *et al.*, 2002). A monitoring station (Campbell Scientific, various sensors) was present on site for basic meteorological data measurement (rainfall, temperature, relative humidity, solar radiation and wind speed).

3.2.2 Plant material

The wetland was planted with 112 stools of S. miyabeana SX67 at a planting density of 2.3 plants/m^2. Salix miyabeana is native to Asia and the cultivar SX67 was developed at the University of Toronto, in Canada (Cameron et al., 2007). It is usually grown from dormant cuttings, and only male clones with no seed production are produced (Cameron et al., 2007). Although it can reproduce vegetatively, it does not propagate laterally (e.g. stolon), so the planting density does not change over time. However, the stools produce new stems when they are cut back. They produce 6 stems on average (Tharakan et al., 2005), ranging from 2 to 12 (Fontana et al., 2016). Tharakan et al. (2016) reported a mean leaf area index of 4.9 for this cultivar at the end of a three-year rotation cycle. SX67 present stomata on both abaxial and adaxial sides of leaves (amphistomatic) at the early development stage, and adaxial stomatal density decreases as the leaves mature (Fontana et al., 2017).

3.2.3 Physiological measurements

To model transpiration of *S. miyabeana*, we measured two main physiological parameters, *i.e.* stomatal conductance and leaf area index.

3.2.3.1 Stomatal conductance

Instant stomatal conductance ($\bar{g}_s$), representing the exchange rate of vapor water from leaf to the boundary layer (mmol m^{-2} s^{-1}), was sampled on the abaxial side of leaves using a steady state porometer (Decagon, SC-1). In 2016, we sampled $\bar{g}_s$ on 34 days from May 15 to October 11, with measurements in the lower, middle and upper parts of the canopy, both inside and at the border of the wetland, and from 6 AM to 9 PM, for a total of 4003 measurements. Data from 2016 allowed us to optimize sampling for the 2017 campaign, with measurements performed from 10 AM to 2 PM, where mean values of $\bar{g}_s$ were observed, and only in middle and upper part of the canopy, because of the low influence of the lower part in the general stomatal conductance ($\bar{G}_s$) of the wetland. In 2017, sampling took place on 43 days from May 11 to October 27, for a total of 3579 measurements. Also, because *S. miyabeana* presents amphistomatic characteristics (Fontana *& al*., 2017), 150 measurements were made on both adaxial and abaxial sides of the leaves (75 pairs of measurements, taken on four days from May to August 2017) to establish a ratio of transpiration occurring on the upper versus the lower side of the leaf.

3.2.3.2 Leaf area index

Leaf area index (LAI), which expresses the leaf area covering a given ground area (m^2 leaf/m^2 ground), was estimated once a month, in the middle of the month, from May to November and for both growing seasons. We calculated the LAI of the entire wetland based on extrapolation of individual willow leaf area and considering that there could be a significant difference between leaf area of willows growing on the border and those growing in the center of the wetland:

$$LAI = (N_{border}LA_{w_{border}} + N_{center}LA_{w_{center}})/A_{wetland} \qquad \text{(Eq. 1)}$$

Where N is the number of willows growing either on the border or in the center, and mean leaf area per willow (LA_w), and $A_{wetland}$ is the wetland area. For our wetland, we considered only the willows growing directly at the edges as the "border section", which represented 40 willows, compared 72 growing in the center, and a border width of 0.75 m. LA_w was estimated for 15 individual willows, seven growing on the border of the wetland and eight growing in the center, as follows:

$$LA_w = A_{leaf}(S_{<1m}N_{leaf} + S_{1-3m}N_{leaf} + S_{>3m}N_{leaf}) \qquad \text{(Eq. 2)}$$

A_{leaf} is the average single leaf area and is measured each month based on 30 to 40 randomly collected leaves and using the software, Mesurim Pro v3.4.4.0. The number of stems (S) was counted on the individuals and divided in 3 height classes (<1 m, 1-3 m >3 m). Finally, the average number of leaves (N_{leaf}) present on stems was estimated by direct counting on 5 random stems of each class. Afterwards, we examined the spatial variation of the leaf area by comparing individual area of stools on the edge and stools in the center of the wetland. Because the leaf cover seemed to exceed the actual area of the wetland, we also calculated and adjusted value of LAI based on the projected canopy area (Allen *et al*., 2011).

3.2.4 Evapotranspiration calculation

3.2.4.1 Actual wetland evapotranspiration

To estimate actual ET of the wetland, we used the water balance method, based on the following mathematical equation (Kadlec & Wallace, 2008):

$$ET_{wet} = \frac{Q_i + IQ_p + Q_r - Q_d - Q_o - \Delta L}{A} \qquad \text{(Eq. 3)}$$

Where ET is the ET rate (mm/d), Q_i the influent rate (mm/d), Q_p the precipitation (mm d^{-1}) adjusted by a canopy interception factor (*I; unitless*), Q_r the flowrate of runoff entering the wetland (mm/d), Q_d the underground drainage rate (mm/d), Q_o the effluent rate (mm/d), ΔL the net variation of the water level in the wetland (mm/d) and A the wetland area in m^2 (Figure 2).

We considered an interception factor of 25%, determined with an equation from Martin and Stephen (2005) and based on leaf area index (see section 2.3.2; $I = 3.01LAI + 1.12$), meaning that only 75% of the rainfall reaches the wetland substrate, the rest being evaporated directly from the leaf and thus not considered as tree ET *per se*. As we will demonstrate below, rapid closure of the wetland canopy makes this high interception factor very suitable. Because of the waterproof membrane, it is assumed that Q_r and Q_d are equal to zero. The net water level variation is obtained by multiplying the water level measured in the wetland by the substrate porosity. Water level was measured hourly with two probes (Levelogger Junior Edge, Solinst) placed at two points in the wetland, from May 27 to December 9 in 2016 and from April 21 to November 29 in 2017. Both influent and effluent volume of the willow wetland were monitored with pulse meters (Omega, FTB8000B) throughout the operating season (the system was completely shut down in winter) which represented 214 and 220 days for 2016 and 2017 respectively. Due to a malfunction of the flow meters, 2016 water balance results were probably overestimated, particularly for late-season results (September and October). The meters were conditioned and calibrated by the supplier in 2016 and measurements for 2017 were considered more accurate.

3.2.4.2 Evapotranspiration modelling

In a treatment wetland, there are few limitations on ET. Available energy is greater than direct solar radiation because of both "oasis" and "clothesline" effects (Dotro *et al.*, 2017; Kadlec and Wallace, 2008) that increase ET potential (Allen *et al.*, 1998). Oasis effect provides a vertical energy transfer in the form of sensible heat from the air surrounding the wetland because its moist condition and transpiration make it cooler than the ambient air. The clothesline effect results from the tall wetland plants being surrounded by smaller vegetation and provides a horizontal energy transfer due to wind (Kirkham, 2014). The clothesline effect and the small size of the wetland also increase plant exposure to wind, which results in constant disturbance of the boundary layer of plant leaves (Kadlec and Wallace, 2008), meaning that water vapor excreted by the leaves is automatically replaced with fresh air and transpiration potential increases. As illustrated in Figure 1, water flows out of the wetland only when the water level exceeds 1.2 m (30 cm below the ground surface), meaning that with constant inflow, the wetland substrate should be saturated with water most of the time. Therefore, we hypothesized that water availability is high and that ET is not limited by water stress. Based on these non-limited conditions, we hypothesized that transpiration of willows in a treatment wetland should be highly correlated to stomatal conductance (*i.e.* water vapor exchange rate between leaf and air; $\bar{G}_s$). $\bar{G}_s$ is generally measured in a volume of water per surface of leaf per time unit (*e.g.* mmol m^{-2} s^{-1}), meaning that leaf area capable of transpiring (LAI_{active}) is also required for ET calculation. Because of the relatively constant disturbance of the boundary layer by wind, transpiration rate should also be driven mainly by water vapor pressure deficit (VPD) in the ambient air. Otherwise, the irrigation of the wetland being below the surface, there is no open contact between water and the atmosphere. According to Shuttleworth and Wallace's energy partitioning model (1985), the high average LAI of *S. miyabeana* (> 4 m^2; Tharakan *et al.*, 2016) implies that most of the energy available for ET is intercepted by the willows, reducing soil evaporation potential to close to zero. Therefore, in this study, we assumed that soil evaporation insignificant and that willow transpiration can be treated as ET. Daily ET of *S. miyabeana* grown in a treatment wetland (mm/d) could then be estimated with the following leaf parameter based equation:

$$ET_{SX67} = \bar{G}_s \cdot LAI_{active} \cdot (VPD/p) \qquad \text{(Eq. 4)}$$

Active leaf area can be calculated throughout the season according to the seasonal leaf development curve and the abaxial/adaxial ratio established by measurements presented in section 2.3. Vapor pressure deficit (kPa) is calculated with daily temperature and relative humidity data (Allen *et al.*, 1998) and expressed in a unit less coefficient by dividing it by the sea level barometric pressure (*p*; 101,325 kPa). To estimate stomatal conductance, we chose an empirical approach based on environmental parameters known to influence stomata openings (Buckley and Mott, 2013). We wanted those parameters to be easily accessible, to allow the transpiration rate to be predicted with minimal resources. Through linear regressions, we tested the statistical relation between mean daily stomatal conductance measured on site and the following daily parameters: solar radiation, average and maximal air temperature, average and minimal relative humidity, wind speed and day of the year. Parameters presenting a significant relation with stomatal conductance ($p<0.05$) were combined to predict canopy general conductance as follows:

$$\bar{G}_s = \sum \alpha \bar{g}_s^x \qquad \text{(Eq. 5)}$$

Where partial stomatal conductance ($\bar{g}_s$) was calculated according to previously selected parameters (x) having their own relative influence (α) on the general stomatal conductance of the wetland canopy ($\bar{G}_s$). $\bar{G}s$ (mmol s^{-1} m^{-2}) was first converted in mm per hour unit with a coefficient (0.0648) that we determined based on the molar volume of H_2O (1 mol = 18 ml) and the fact that 1 L represents 1 mm over 1 m^2. Then we expressed $\bar{G}s$ in mm per day unit (mm/d) using the mean monthly hours of bright sunshine per day (HBS).

3.2.4.3 Reference evapotranspiration and plant coefficients

Reference ET was calculated according to the modified Penman-Monteith equation (Allen *& al.*, 1998):

$$ET_0 = \frac{0{,}408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0{,}34u_2)} \qquad \text{(Eq. 6)}$$

In this model, ET_0 is supposed to represent water loss of a surface covered with 12 cm high well-watered turf grass (Allen *& al.*, 1998). Calculation of this value makes it possible to determine crop coefficient (Kadlec and Wallace, 2008):

$$K_{\mathrm{wet/SX67}} = ET_{\mathrm{wet/SX67}} / ET_0 \qquad \text{(Eq. 7)}$$

Where K is the crop, or plant, coefficient, ET is the actual or modelled ET rate of the willow stand as calculated with equation 3 and 4 and ET_0 the reference crop ET provided by equation 6.

3.2.5 Statistical analysis

The relation between meteorological parameters and $\bar{G}s$ was tested with linear, quadratic and power regressions. The influence of parameters on a given variable (e.g. influence of leaf face on $\bar{G}s$ variation) was tested with two-way ANOVAs analysis with a 0.05 significance threshold ($\alpha = 0.05$). LA and stomatal ratio were normalized using a log transformation prior the analysis. Tukey's post-hoc statistical test was used when necessary to better interpret the results of the analysis of variance ($\alpha = 0.05$). All statistical analyses were performed using R 3.5.1 software.

3.3 Results

The summer of 2016 was hot and dry, with a mean temperature of 18.0 °C (± 6.0) and 569 mm of rainfall from May to October. Mean temperature was similar in 2017 (17.9 °C ± 4.8), but with less days on which maximum temperature rose above 30 °C. Also, 2017 saw much higher rainfall, with 819 mm for the same period. A summary of solar radiation, rainfall and daily mean temperature for both growing seasons is shown in Figure 2. Average reference crop ET was 4.5 mm/d in 2016 and 4.1 mm/d in 2017, for a total of 819 mm and 750 mm respectively, from May to November. For the willow wetland, we calculated a mean daily ET rate of 28.7 mm/d and a seasonal total ET of

5047 mm from May 9 to October 31 in 2016, and 16.8 mm/d and a seasonal total of 2860 mm from May 15 to October 31 in 2017 (Figure 4; Tables 1A and 1B).

3.3.1 Physiological measurements

Stomatal conductance values were generally higher and more variable in the 2016 season, with a mean value of 418 (± 124) mmol m^{-2} s^{-1} compared to 309 (± 59) mmol m^{-2} s^{-1} in 2017. The adaxial/abaxial stomatal conductance ratio was relatively high (0.33 ± 0.17) and variable in the early season, decreasing to relatively constant and low values (0.14 ± 0.06) for the rest of the summer (Figure 5).

Thus, overall seasonal transpiration occurring on the upper part (adaxial) of the leaf represents about 20% of that on the lower side (abaxial), and actual stomatal conductance equals approximately 120% of the values measured on the abaxial side of the leaf only. In both the 2016 and 2017 seasons, leaf cover established rapidly, attaining its highest value in July, with 10.4 and 11.4 m^2 of leaves per m^2 of soil respectively. The canopy extended beyond the wetland borders by about 50 cm meter on each side, for a projected canopy area of 63 m^2 compared to the actual wetland area of 48 m^2. Peak LAI measured using the projected canopy area was 7.9 in 2016 and 8.7 in 2017. In 2017, the global leaf area was a little higher than in 2016, attained its maximal value earlier and retained active foliage later in the season (Figure 6). Trees on the edge of the wetland grew up to three times more stems and leaf area than those in the center (Figure 7).

3.3.2 Evapotranspiration modelling

We found a significant effect of temperature, solar radiation, relative humidity and day of the year on stomatal conductance (Table 2), but no effect of wind speed. For temperature and relative humidity, mean daily values were better predictors than maximum and minimum values respectively. Correlation between $\bar{G}_s$ and each factor separately was relatively weak (r^2 from 0.05 to 0.21), but together they explained half of stomatal conductance variation throughout the season (Figure 8), which can be considered satisfying due to the many other factors driving this parameter but not measured here (Buckley and Mott, 2013).

The stomatal conductance predictive model, based on equation 5 and using mathematical relations presented in Table 2, was good at predicting mean $\bar{G}_s$, with a predicted mean seasonal value of 428 mmol m^{-2} s^{-1} over 418 mmol m^{-2} s^{-1} measured in 2016, and 329 mmol m^{-2} s^{-1} predicted over 309 mmol m^{-2} s^{-1} measured in 2017. Daily variation was captured more accurately in 2017 than in 2016 (Figure 9).

Using the general stomatal conductance calculated with equation 4 and the previously established leaf area parameters, we calculated the ET rate (Eq. 3) and the corresponding crop coefficient (Eq. 6; Table 1A and 1B). Modelled willow ET was higher in 2016, as was reference ET, with a mean daily rate of 19.5 mm/d compared to 13.5 mm/d in 2017 (Table 1A and 1B). Calculated seasonal ET was 3434 mm in 2016 and 2361 mm in 2017 (Figure 4). Crop coefficients were also higher in 2016 than in 2017, with an average value of 5.2 and 3.1 respectively (Tables 1A and 1B). Highest daily ET rates were calculated in August in 2016 (44.8 mm/d on August 13) and in July in 2017 (34.3 mm/d). Modelled ET results are very close to those calculated with the water balance for most of the 2017 season (Figure 4), but lower than water balance ET in 2016, probably due to the overestimation of actual ET for this season (section 2.4.1).

3.4 Discussion

The mean monthly ET rate measured by water balance for *Salix miyabeana* in treatment wetland conditions ranged from 22.7 to 38.8 mm/d in 2016 and from 9.7 to 28.7 mm/d in 2017, with a mean seasonal cumulative ET of 5047 mm in 2016 and 2860 mm in 2017. Crop coefficients were also higher in 2016 than in 2017, with an average value of 7.7 and 5.1 respectively. These results are higher than those reported in the very few studies conducted in comparable conditions but in different climate, while our modelled results are similar (Curneen and Gill, 2014; Gregersen and Brix, 2001; Brix and Arias, 2005; Kučerová *et al.*, 2001; Table 3). However, both measured and modelled results presented here are even higher in comparison to the only study we found for another cultivar of *S. miyabeana* (SX64; Mirck and Volk, 2009; Table 3), grown in open field plantation, with low water input and soil contamination, but in a very similar climate.

Average seasonal ET rates reported for other fast-growing willow cultivars grown in field plantation are also generally much lower than our results (1.4 mm/d, Linderson et al., 2007; 3.0 mm/d, Lindroth et al., 1994; 2.9 mm/d, Personn, 1995; 1.0 mm/d, Mata-Gonzalez; 3.1 mm/d, Budny and Benscoter, 2012). In comparison, similar rates (from 10 to 23 mm/d) were measured for young *S. babylonica* grown in water saturated conditions in the north-eastern United States (Pauliukonis *et al.*, 2001). Such high ET rates can be explained by both enhancing factors linked to the treatment wetland itself (*i.e.* oasis and clothesline effect, high water availability, important border effect) and by *S. miyabeana* ecophysiology (*i.e.* high stomatal conductance and leaf area index).

In this study, a simple model based mainly on two leaf parameters (stomatal conductance and leaf area index) was sufficient to model ET. As expected, the model ET results were lower than the water balance results in 2016 (see section 2.4.1). However, 2017 simulation results closely resembled water balance results (Figure 3). The fact that our simplified ET model yielded conclusive results supports our premise that typical ET limiting factors like water and energy availability are greatly attenuated in small wetlands. Other studies presenting ET modelling methods for willows often include several limiting factors (Irmak et al., 2013, Iritz et al., 2001), ignore heat advection effect (Přibáň and Ondok, 1986) or focus on soil hydrology (Personn, 1995, Hartwich *et al.*, 2016; Borek et al., 2010) or complex physiological processes (Tallis et al., 2013). Although based on sound scientific assumptions, those models hardly apply in treatment wetland conditions where water level typically ensures a high water availability and heat advection effect is very important (increased available energy). The few input parameters required for operation of the model also represent simple method for managers working with treatment wetlands to include ET estimation in their planning activities. However, to be used for other taxa, a basic knowledge of the LAI dynamic and general stomatal conductance for the species is needed, and could require additional $\bar{g}_s$ measurement in the field to adjust the model.

Regarding ET related characteristics specific to *S. miyabeana*, we found that mean stomatal conductance (0.4 mol m^{-2} s^{-1}) was consistent with published results for other willows (0.4 mol m^{-2} s^{-1}, Budny and Benscoter, 2016; 0.2-0.7 mol m^{-2} s^{-1}, Hall *et al.*, 1998), or higher (0.2 mol m^{-2} s^{-1}, Kučerová *et al.*, 2001). Leaf area index values were higher than those reported in the literature for other willow cultivars, even when using the projected canopy area for the calculation (Figure 10).

As for stomatal conductance, it is also interesting to note that the highest mean daily value measured (661 mmol m^{-2} s^{-1}) is much higher than the values proposed for deciduous trees and even plants from wet habitats (Jones, 2013). The ratio between the conductance of the upper and lower side of the leaf is consistent with the literature predicting higher adaxial activity or adaxial stomatal density in younger leaves (Fontana *et al.*, 2017). Meteorological factors could only explain about half of the stomatal conductance values and variability. Stomatal aperture is also driven by many biochemical and environmental factors (Buckley and Mott, 2013) that were not studied here. Aging of the willows, or negative effects of contaminant accumulation in the substrate are also factors that affect long-term variability of $\bar{G}_s$ in a wetland, and should be considered. A sampling campaign (data not shown) conducted in June of 2017 in Denmark on *S. viminalis* clones used for zero-discharge wetlands showed significantly greater stomatal conductance in willows recently coppiced, compared to older individuals growing in the exact same conditions, which supports the aging hypothesis. Such factors should be investigated thoroughly in the future. Leaf area of the willow wetland attained its maximal value (complete canopy closure) with two-year-old shoots, peaking in July at around 12 m^2 of leaves per m^2 of ground. Planting density and methodological differences could partially explain why LAI of our wetland was very high compared to findings reported in the literature. Furthermore, all results presented in Figure 8 are based on field plantation or natural river bands of much greater size than our wetland, and the effect of increased leaf area at the border is negligible. In our wetland, trees growing on the border had more space and light resources available to support their growth, which explains the significant leaf area difference we observed for trees growing at the border of the wetland compared to those in the middle, that are laterally limited by the growth and light interception by their neighbours. Our finding comparing individual leaf area at the edges versus in the center of the wetland is also interesting, because it means we could modulate ET rate directly in the wetland design. Indeed, if ET is directly related to LAI as demonstrated here, adjusting the edge or aspect ratio of the surface area of a wetland could enhance (higher ratio) or limit (lower ratio) ET per ground unit, according to management objectives. Fertilization applied at the beginning of 2017 seemed to have accelerated the establishment of the leaf cover but did not significantly increase maximal LAI. Since the fertilizer used consisted of solid granules applied directly on the soil, with dissolution regulated by rainfall and temperature, it is possible that rapid closure of the canopy and high rain interception by willows prevented the fertilizer from dissolving appropriately and penetrating the substrate. In 2016, the canopy already seemed completely closed by mid-season and it is possible that maximum leaf area index was already attained. Indeed, in 2017, stems grew higher but there was little or no leaf development at the bottom of the stems (as was observed in 2016), probably because canopy closure was achieved and all available light was intercepted in the upper part of the trees. Therefore, we conclude that maximal LAI was achieved with two-year-old shoots, without a need for fertilization, and that coppicing should be scheduled on a two-year basis.

3.5 Conclusions

S. miyabeana ET in treatment wetland conditions was very high throughout this study. We highlighted several factors related to treatment wetlands that can significantly increase potential ET. Because there are few limitations on ET in wetlands, a model exclusively based on leaf parameters successfully predicted ET values and calculated crop coefficients for the studied willow wetland. Because these results are based on a full-scale wetland, they can be used as design parameters for treatment wetlands using *S. miyabeana,* and the equation presented for ET calculation can be adjusted for other fast-growing willow species used in similar growing conditions. However as we demonstrated earlier, the edge effect on evapotranspiration through leaf area, clothesline and oasis effects should be taken into consideration prior to extrapolating from our results. We also presented a strategy to optimize ET per ground area by changing the aspect ratio of the wetland (and consequently its leaf area index) as well as regularly coppicing the stems. In the future, other parameters that may affect ET in treatment wetlands, such as tree aging, substrate type and contaminant toxicity, could be investigated. This study is a first step towards better ecophysiological characterization of woody plants used in treatment wetlands.

Acknowledgments

This work was supported by the NSERC/Hydro-Québec Industrial Research Chair.

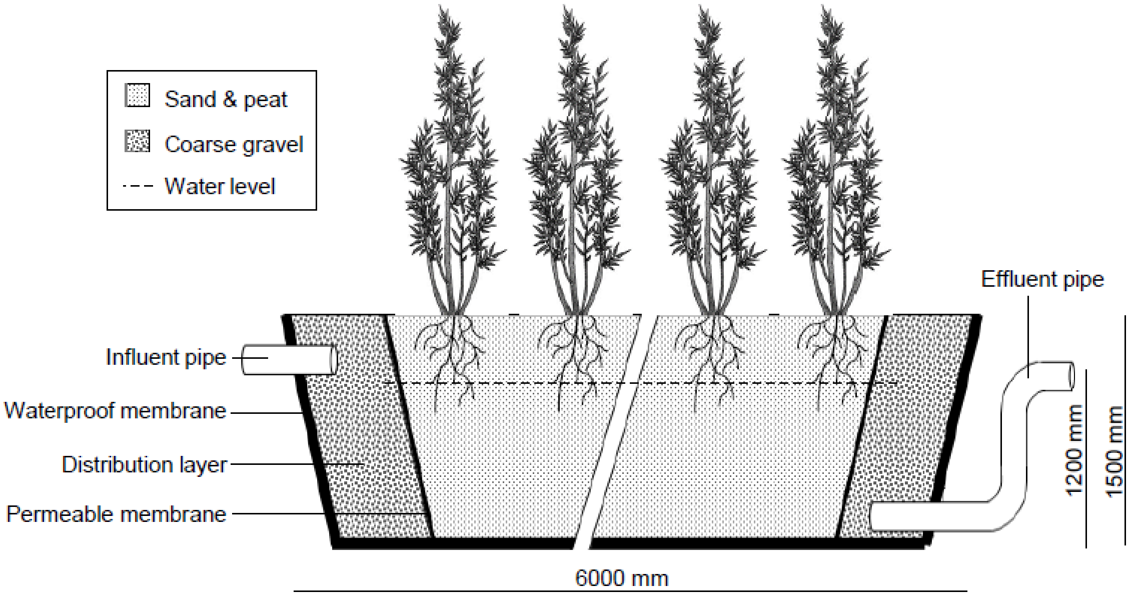

Figure 3.1 Section view of the horizontal subsurface flow wetland used to measure and model evapotranspiration of *S. miyabeana* in treatment wetland conditions.

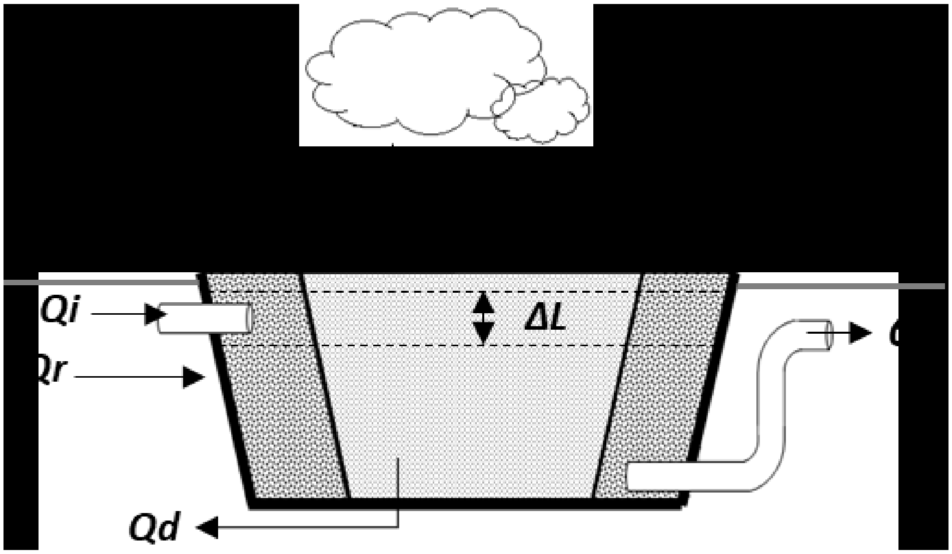

Figure 3.2 Schematic representation of the components of a typical water balance equation. *ΔL*: water level variation, *Qd*: drainage, *Qe*: effluent, *Qi*: influent, *Qp*: precipitation, *Qr*: runoff. In a treatment wetland lined with waterproof material (as depicted in this Figure), runoff and drainage components are not relevant.

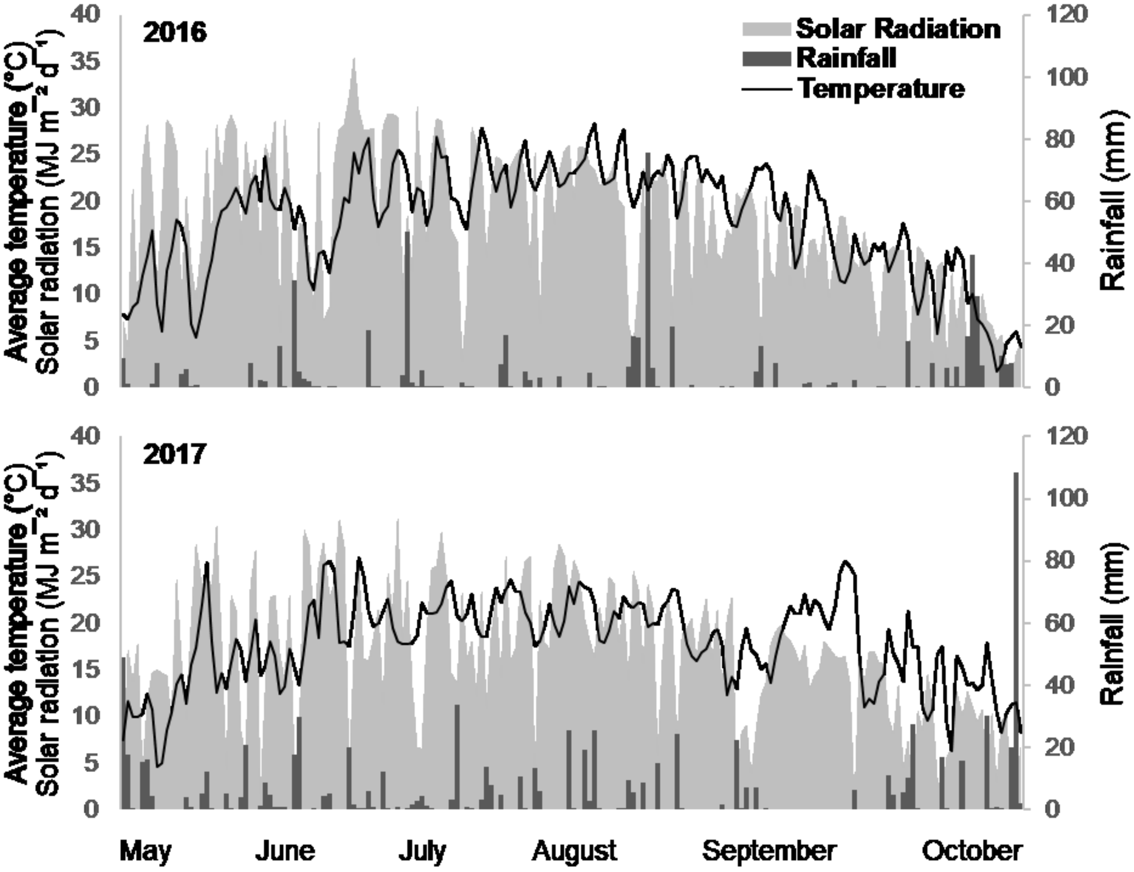

Figure 3.3 Summary of the meteorological conditions at the experimental site for the 2016 and 2017 growing seasons.

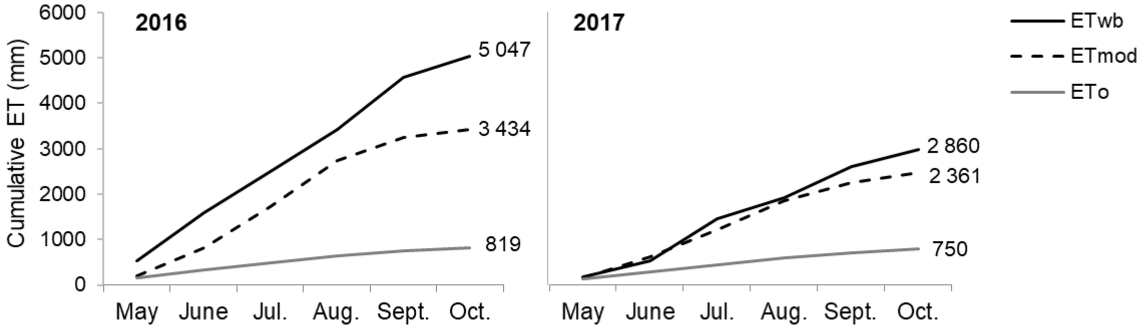

Figure 3.4 Seasonal cumulative evapotranspiration of a 48 m² willow wetland calculated by water balance (ETwb) and modelling (ETmod) for 2016 and 2017 vegetation seasons. Penman-Montheith reference evapotranspiration (ETo) is also reported for the same period.

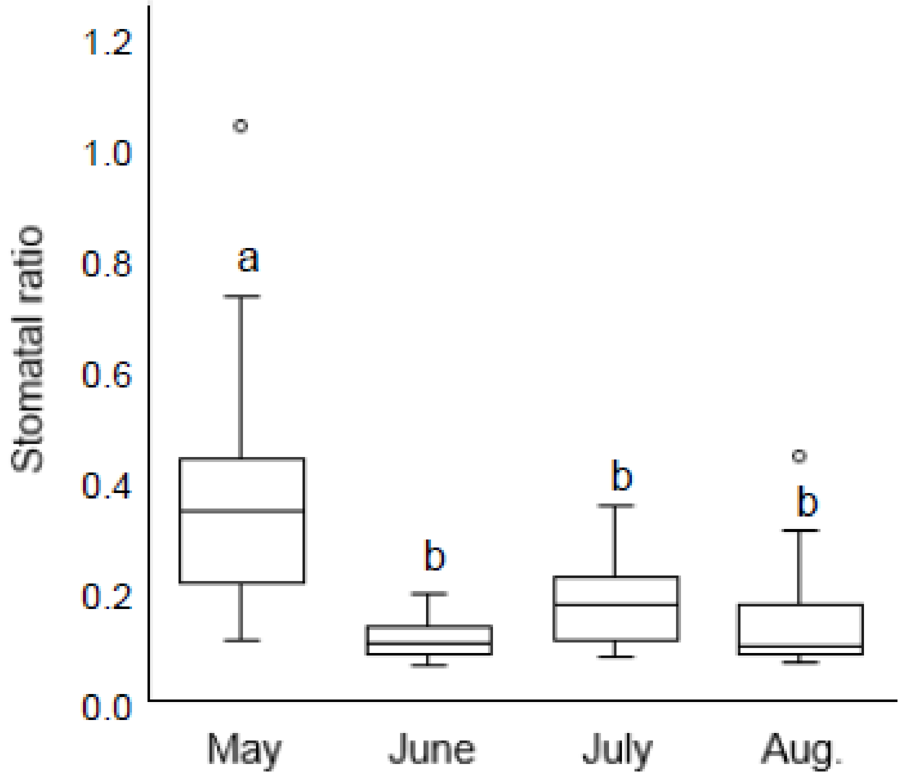

Figure 3.5 Adaxial/abaxial stomatal conductance ratio of *S. miyabeana* growing in treatment wetland conditions for the 2017 summer season. Different letters represent statistically different values.

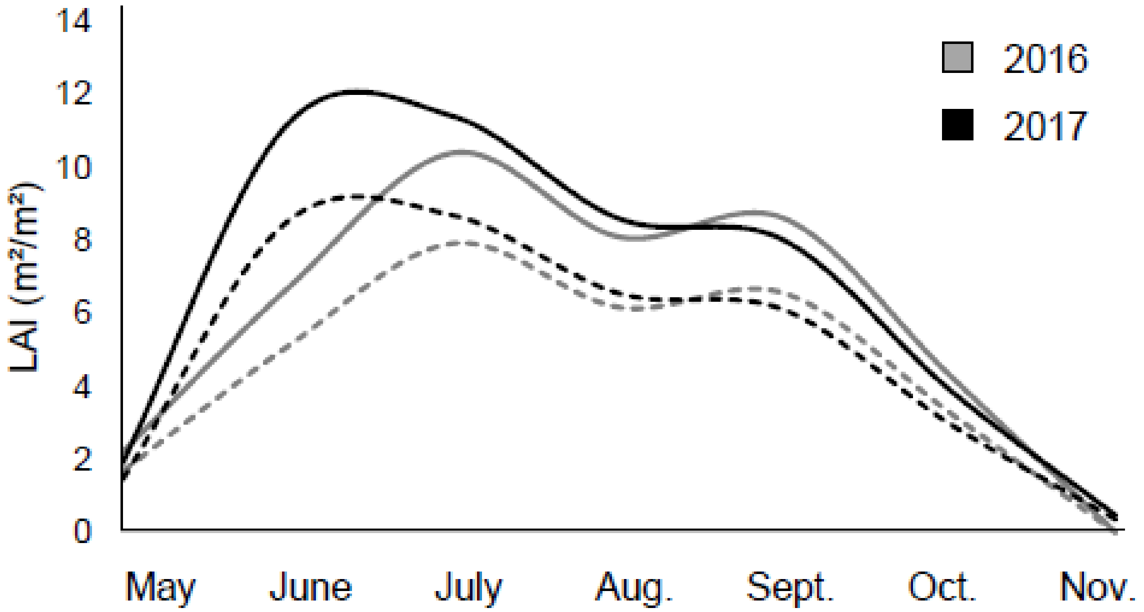

Figure 3.6 Evolution of the leaf area index of a 48 m² wetland (solid line) planted with *S. miyabeana* throughout 2 successive growing seasons, and the corresponding values adjusted for a 63 m² projected canopy area (dashed line).

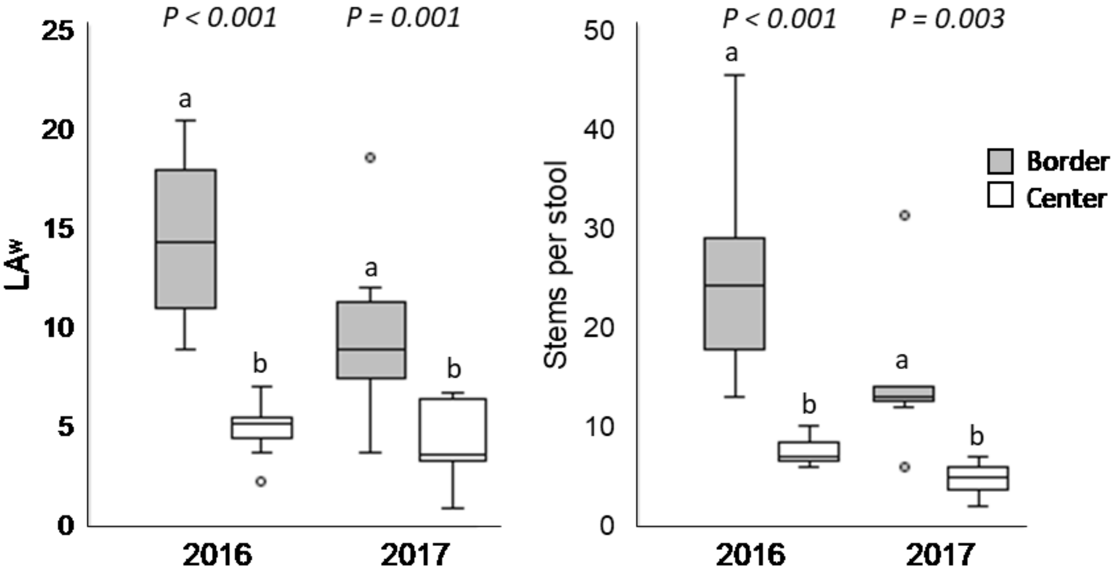

Figure 3.7 Leaf area (LA_w) and number of stems per stool of 15 *S. miyabeana* individuals growing either at the border or in the center of a 48 m² constructed wetland, measured in the month of July, in 2016 and 2017. Different letters represent statistically different values.

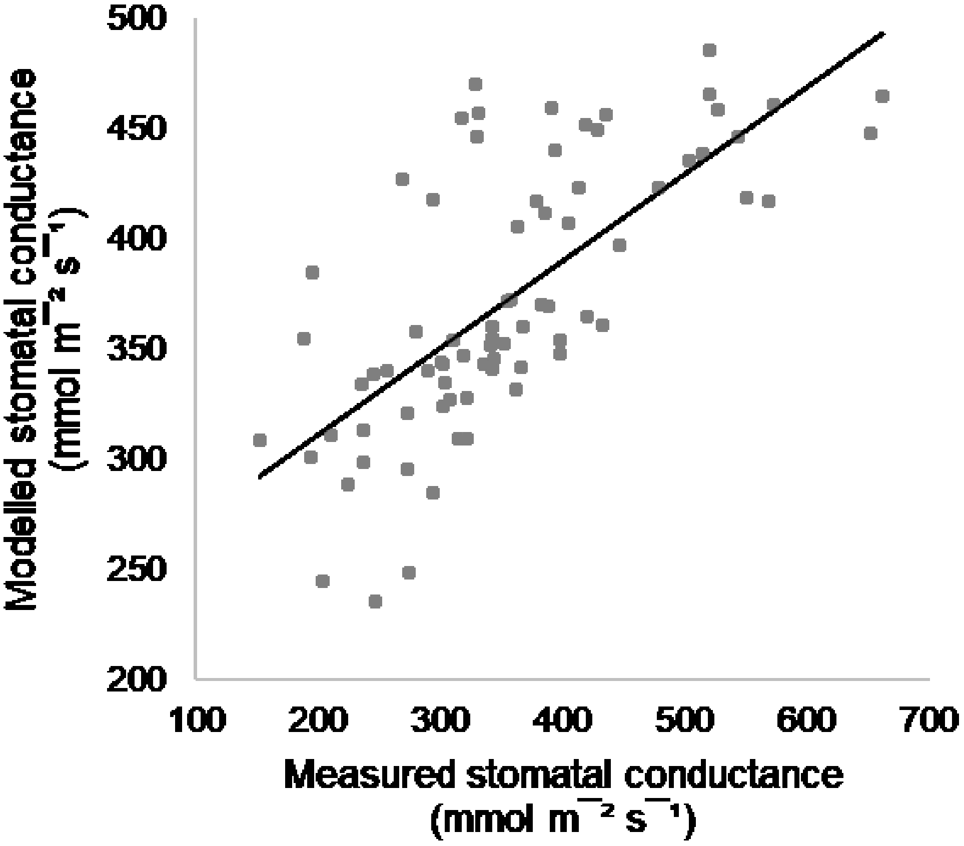

Figure 3.8 Results of $\bar{G}_s$ modelling, based on temperature, solar radiation, relative humidity and day of year, compared to $\bar{G}_s$ measured on the field under the same parameters.

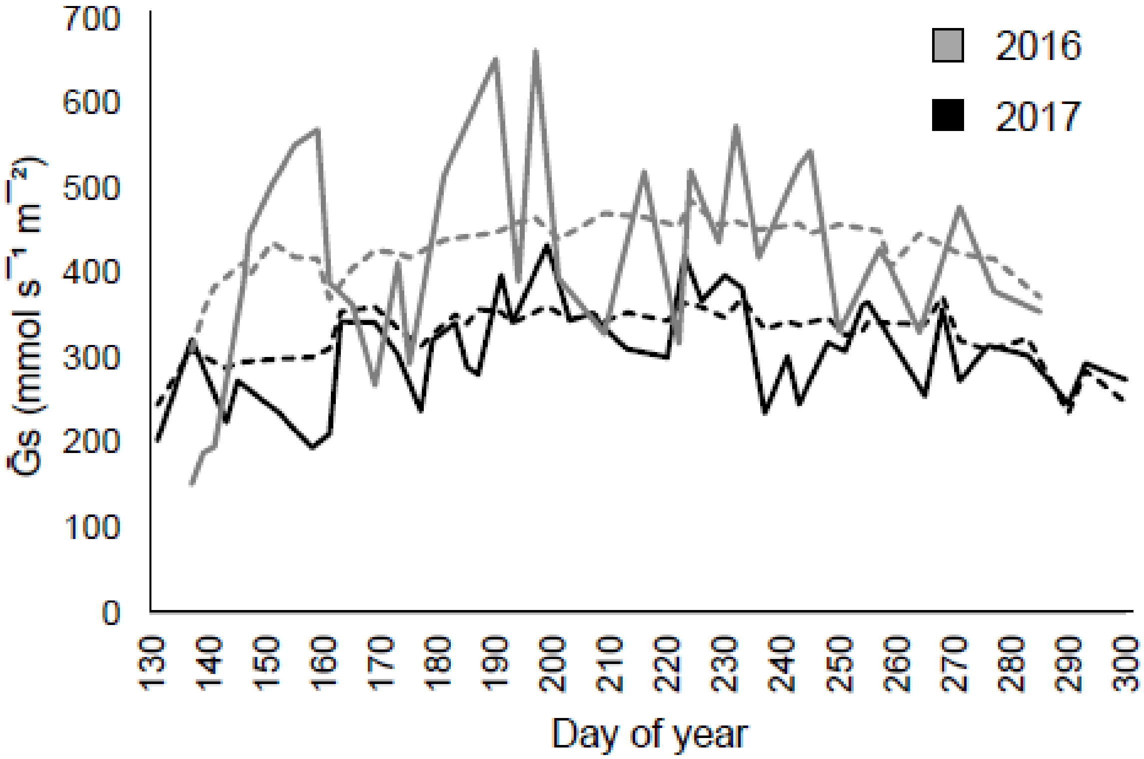

Figure 3.9 Stomatal conductance (Ḡs) field measurements (solid line) and modelling results (dashed line) over the 2016 and 2017 growing seasons.

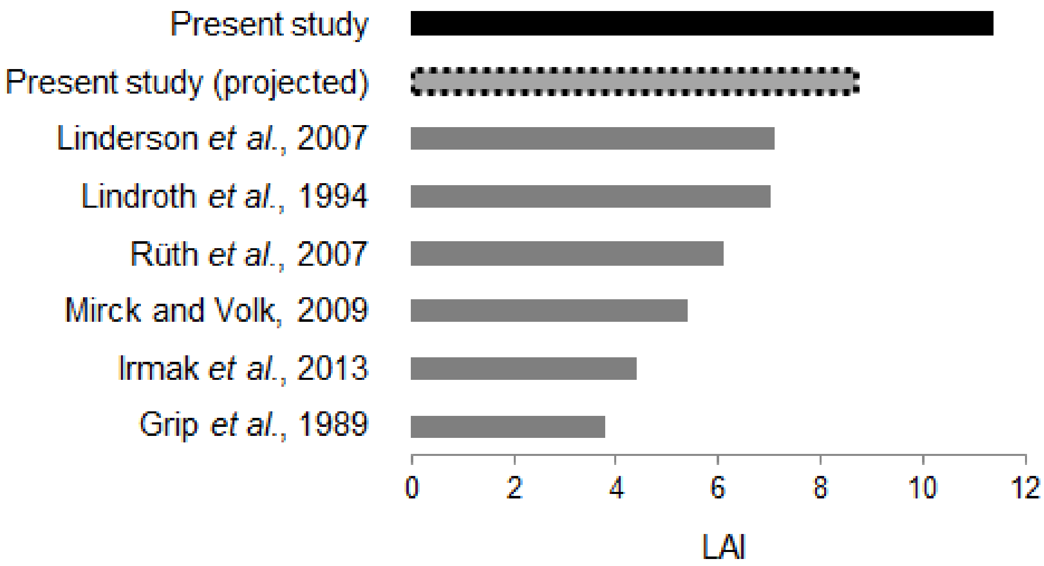

Figure 3.10 Maximal leaf area index (LAI) reported for willow stands (different cultivars) in various studies including the present results, and the corresponding value adjusted with projected canopy area.

Table 3.1A. Mean daily Penman-Monteith reference evapotranspiration (ET_0), active leaf area index of the 48 m^2 treatment wetland (LAI), actual wetland (ET_{wet}) and modelled willow evapotranspiration (ET_{SX67}) and crop coefficient (K_{wet} and K_{SX67}) presented as monthly and seasonal averages, for the 2016 growing seasons.

	ET_0	**LAI_{active}**	ET_{wet}	K_{wet}	**ET_{SX67}**	**$K_{(SX67)}$**
May	5.2 ± 1.6	3.3 ± 1.3	22.7 ± 18.0	4.2 ± 3.0	8.9 ± 6.6	1.8 ± 1.3
June	5.5 ± 2.4	8.2 ± 1.4	35.6 ± 23.9	9.0 ± 9.7	20.8 ± 10.5	5.2 ± 3.8
July	5.4 ± 1.7	11.6 ± 0.5	29.5 ± 12.1	6.7 ± 5.8	30.0 ± 10.7	6.8 ± 5.8
August	5.0 ± 1.6	10.1 ± 0.3	29.5 ± 19.6	6.2 ± 3.9	32.3 ± 10.8	8.2 ± 7.8
Sept.	3.9 ± 0.9	9.5 ± 0.9	38.8 ± 20.4	11.4 ± 10.7	17.2 ± 6.1	4.7 ± 2.4
October	1.8 ± 1.0	4.5 ± 1.9	32.1 ± 30.1	29.5 ± 45.3	6.1 ± 2.6	3.7 ± 2.7
Average	**4.5 ± 2.1**	**7.9 ± 3.2**	**28.7 ± 25.6**	**7.7 ± 26.0**	**19.5 ± 13.1**	**5.2 ± 5.0**

*Values overestimated due to flow-meter malfunctioning.

Table 3.1B. Mean daily Penman-Monteith reference evapotranspiration (ET0), active leaf area index of the 48 m^2 treatment wetland (LAI), actual wetland (ET_{wet}) and modelled willow evapotranspiration (ET_{SX67}) and crop coefficient (K_{wet} and K_{SX67}) presented as monthly and seasonal averages, for the 2017 growing seasons.

	ET_0	**LAI_{active}**	**ET_{wet}**	K_{wet}	**ET_{SX67}**	**$K_{(SX67)}$**
May	3.9 ± 2.1	3.4 ± 1.9	9.7 ± 0.9	2.8 ± 1.9	8.6 ± 5.4	1.8 ± 0.7
June	5.0 ± 2.1	12.1 ± 2.0	11.5 ± 1.4	3.1 ± 2.0	14.4 ± 7.1	2.9 ± 0.8
July	4.9 ± 1.6	13.3 ± 0.5	28.7 ± 17.2	7.0 ± 5.4	18.6 ± 6.4	4.1 ± 1.3

August	4.7 ± 1.2	10.7 ± 0.7	14.3 ± 10.2	3.4 ± 3.2	20.1 ± 4.7	4.1 ± 0.7
Sept.	3.6 ± 1.1	9.1 ± 0.8	21.8 ± 4.4	6.9 ± 4.4	12.9 ± 4.7	3.5 ± 0.9
October	2.3 ± 1.0	4.8 ± 1.4	11.8 ± 6.0	6.1 ± 6.3	6.3 ± 4.5	2.4 ± 1.2
Average	**4.1 ± 1.7**	**8.9 ± 3.9**	**16.8 ± 11.3**	**5.1 ± 4.6**	**13.5 ± 7.4**	**3.1 ± 1.2**

Table 3.2 Parameters of the relations found between stomatal conductance of *S. miyabeana* and temperature (T), day of year (DOY), solar radiation (Rad) and relative humidity (RH). Parameter importance (α) and predictive equations used for stomatal conductance modelling are presented.

Parameter	**Type of relation**	$\mathbf{p_{value}}$	$\mathbf{R^2}$	**α**	**Equation**
T	Power	<0.001	0.21	0.48	$88.4x^{0.5}$
DOY	Quadratic	0.002	0.13	0.30	$-0.02x^2 + 9x - 572$
Rad	Quadratic	0.05	0.05	0.11	$-0.005x^2 + 2x - 177$
RH	Linear	0.03	0.05	0.11	$2.9x + 168$

Table 3.3 Evapotranspiration results obtained for fast growing willow in treatment wetland conditions (ref. 1 to 4) or in open field plantation (ref. 5)

Species (cultivar)	**Country**	**Seasonal ET**	**Peak K_{ET}**	**Seasonal K_{ET}**	**Annual K_{ET}**	**Ref.**
S. miyabeana (SX67)	Canada (QC)					1
Measured		3954 mm	9	6.4	3.7	
Modelled		2897 mm	8.2	4.2	2.5	
S. viminalis (Bjorn, Tora, Jorr)	Denmark	1113 mm	-	-	2.5	2
S. viminalis	Ireland	669 mm	5.1	3.0	-	3
S. cinerea	Belgium	-	6.7	-	-	4
S. miyabeana (SX64)	USA (NY)	515 mm	1.4	1.2	-	5

Ref. 1: present article; 2: Gregersen and Brix, 2001; 3: Curneen and Gill, 2014, 4: Kučerová et al., 2001; 5: Mirck and Volk, 2009.

Chapitre 4 | Ecophysiological responses of a willow cultivar (*Salix miyabeana* 'SX67') irrigated with treated wood leachate

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Status : Accepted for publication in *Water, Air & Soil Pollution*

Reference : Frédette, C., Comeau, Y., & Brisson, J. (2019). Ecophysiological responses of a willow cultivar (*Salix miyabeana* 'SX67') irrigated with treated wood leachate. *Water, Air & Soil Pollution*, in press.

Abstract

As wood preservatives leach from exposed treated wood, they contaminate soil and water, creating an environmental problem that needs to be addressed. Treating this contamination is particularly challenging since it includes mixed compounds, such as heavy metals and trace elements, as well as xenobiotic organic pollutants like polychlorinated dibenzo-dioxin/furan congeners (PCDD/Fs) that are very toxic and are under very strict discharge regulations. Cultivating fast growing willow shrubs, either in soil or in treatment wetlands, offers a flexible and inexpensive treatment option. The main objective of this study was to evaluate the tolerance of a frequently used willow cultivar (*Salix miyabeana* 'SX67') to irrigation with leachate contaminated with pentachlorophenol (PCP) and chromated chromium arsenate (CCA), two important wood preservatives. We designed a mesocosms experiment with willow grown in three different substrates and irrigated over twelve weeks with three different leachate concentrations. Willow proved to be tolerant to irrigation with the raw leachate, with only leaf area decreasing with increasing leachate concentration. However, the type of growing substrate influenced willow ecophysiological responses and overall performance, and seemed to affect contaminant dynamics in the plant-soil system. All contaminants accumulated in willow roots, and Cu and PCDD/Fs were also translocated to aerial parts. Overall, this study suggests that *Salix miyabeana* 'SX67' could be a good candidate for treating water or soil contaminated with wood preservatives.

Keywords: phytotoxicity, phytoremediation, wood preservatives, pentachlorophenol (PCP), chromated copper arsenate (CCA), polychlorinated dibenzo-dioxins/furans (PCDD/Fs)

4.1 Introduction

Canada has one of the world's largest wood preservation industries, along with the United States and the United Kingdom (Morris and Wang, 2006). The nature of wood preservatives has changed over time, and pentachlorophenol (PCP), an oil-borne substance that was commonly used in the 1950s, was gradually replaced by water-borne chemicals such as chromated chromium arsenate (CCA; Environment Canada, 2013), because of its toxicity (WHO, 1987; NTP, 2016). Following public apprehension about the presence of the toxic compound arsenic in the preservatives, CCA was banned from residential use in 2004 in both Canada and the United States (Morrell, 2017). Nonetheless, both CCA and PCP are still permitted for industrial use, including utility wood pole treatment (ATSDR, 2001; Morris and Wang, 2006; Environment Canada, 2013).

During the wood treatment process, or while in use or storage, treated wood exposed to rain events generates leachates that are contaminated with wood preservatives. Although leaching rate and susceptibility over time are often debated, soils at wood treatment facilities and final storage locations have clearly been shown to be contaminated (Bhattacharya *et al*., 2001; Kitunen *et al*., 1987; Stilwell and Gorny, 1997; Valo *et al*., 1984; Zagury *et al*., 2003). Chromium (Cr), copper (Cu) and chlorophenols (CP) seem to be more mobile in the soil, and can potentially reach aquifers of aquatic ecosystems.

Arsenic (As) and PCP associated hydrocarbon compounds such as polychlorinated dibenzo-dioxins/furans (PCDD/Fs) are less mobile, but very persistent in the soil (Bhattacharya *et al*., 2001; Kitunen *et al*., 1987).

Phytoremediation has been proposed as a technology with potential to address such soil contamination. Willows and similar fast growing woody species like poplar have been studied specifically for remediation of these types of pollutants (Mills *et al.*, 2006; Önneby, 2006), along with various herbaceous plants. Preventive approaches, such as intercepting the contaminated leachates prior to their release in the soil also represent a sustainable avenue; the intercepted leachates must then be treated to meet water discharge regulations. Treatment wetlands are a proven technology that can be designed to treat various types of wastewaters, including those containing metallic trace elements, chlorinated compounds and hydrocarbons (Kadlec and Wallace, 2008). Recently, an experimental study showed that mixed wood preservatives leachate (PCP and CCA) can be treated successfully with horizontal sub-surface flow wetlands (Lévesque *et al.*, 2017). Designing zero liquid discharge willow wetlands has also been identified as a solution for treating this type of leachate and eliminating the risk of releasing contamination in the environment (Frédette *et al.*, 2019).

If willows are to be used for the treatment of either soil or water contaminated with wood preservatives, it is important to study the effect of those contaminants on willows. Tolerance and toxicity studies have been conducted at laboratory scale in hydroponic solutions for some wood preservative compounds such as As (Purdy and Smart, 2008), Cr (Yu and Gu, 2007; Yu *et al*., 2008) and derivatives of PCP (Clausen *et al*., 2018; Ucisik and Trapp, 2008; Ucisik *et al*., 2007). However, pollutant dynamics are much more complex in soils or substrates, and the presence of mixed contamination could lead to different results than if each contaminant were treated separately. The objective of this mesocosm study was to investigate the potential effects of water contaminated with both ACC and PCP on a willow species frequently used in phytoremediation and treatment wetlands, *Salix miyabeana* 'SX67'. We were particularly interested in physiological parameters associated with biomass production and treatment performance. Furthermore, we wanted to test the influence of different growing media, on the premise that different substrates would demonstrate differences in water holding capacity, nutrient sink in the root zone, and pollutant dynamics, which could in turn influence plant ecophysiological responses (particularly in CCA contaminated systems; Balasoiu *et al.* 2001; Girouard and Zagury, 2009).

4.2 Methods

4.2.1 Experimental set-up and treatments

This study was conducted in a greenhouse located at the Montréal Botanical Garden (45°33'39.6"N 73°34'19.2"W), in eastern Canada. Each experimental unit consisted of a cylindric lysimeter 0.53 m high and 0.37 m in diameter (0.11 m^2 top area), filled with substrate and planted with one *Salix miyabeana* SX67 individual (Figure 1a). We specifically chose large containers with a depth greater than the expected average root zone (50 cm deep pots compared to an expected average 30 cm root zone for shrub willows) in order to minimize any root development constraint effect. Plant density calculated according to the surface area of our containers was relatively high (10 plants/m^2), but has been observed in willow plantations (Bullard *et al.*, 2002). The distance between each pot (Figure 1c) also helped prevent canopy competition for light interception. Six treatments were tested: sand substrate irrigated with various leachate dilutions (S0, S25, S50 and S100), sand topped with a coco fiber substrate layer irrigated with the 25% leachate dilution (C25) and sand topped with an organic substrate layer irrigated with the 25% leachate dilution (O25). Each treatment was replicated three times and one lysimeter filled only with sand remained unplanted to estimate soil evaporation, for a total of 19 lysimeters. Figures 1b and 1c present the experimental treatments and spatial disposition of the 19 lysimeters in the greenhouse. A one-inch wide tube, pierced only in the bottom 5 cm, was placed in the units for irrigation and water sampling (Figure 1a). There was no outflow from the lysimeters, so all water loss could be attributed to evapotranspiration. Willow shrubs were grown in pots from cuttings in the summer of 2017 and transplanted in the lysimeters in August of the same year. Temperature in the greenhouse was adjusted to meet outside temperature but could not be brought below 5°C in winter.

The first layer of the substrate consisted of 8 cm of coarse granitic gravel (16-32 mm) for drainage, topped with either 40 cm of sand or 20 cm of sand topped with one of two other substrates to be tested (*organic* and *coco fiber*), and then covered with 2 cm of fragmented rameal wood as a mulch to limit soil evaporation. The *sand* substrate consisted of washed coarse sand (0.5-1 mm); the *coco fiber* substrate of 80% coconut fiber and 20% coarse sand; and the organic substrate of an assemblage of 60% black earth (Quali Grow, 0.2-0.2-0.1 NPK), 20% potting soil (Fafard, 0.3-0.1-0.4 NPK) and 20% coarse sand. The porosity measurements made in the laboratory for the sand, coco fiber and organic substrates were 36%, 70% and 39% (volume based), respectively. The objective of using three different substrates was to evaluate if different porosities, water retention capacities (WRC) and organic matter (OM) contents would influence willows response (Balasoiu *et al*., 2001; Dobran and Zagury, 2006), based on the premise of the following gradient : WRC and OM of organic substrate > WRC and OM of coco fiber substrate > WRC and OM of sand substrate.

The raw leachate was collected from a treated wood pole storage site on June 15 (batch 1) and August 6 (batch 2), and stored in 20 L polyethylene tanks at 4°C. Both old PCP treated and new CCA treated wood poles are stored at this specific site. Consequently, chlorophenolic compounds from the PCP (as well as PCDD/Fs that are present in commercial PCP formulations), and As, Cr and Cu from the CCA were expected to be present in the leachate (Lorber *et al*., 2002; Frédette *et al.*, 2019). All the contaminants targeted were present in the leachate, except for pentachlorophenol, which had already begun to degrade into dichlorophenol, but concentrations of this compound were much higher in batch 2 (Table 1). Three lysimeters filled only with sand were irrigated with the raw leachate (100%, S100), three with a first dilution of the leachate (50%, S50), three with a second dilution (25%, S25), and three with tap water only (S0). The six lysimeters filled with *organic* substrate and *coco fiber* were then irrigated with the second dilution (25%, O25 and C25). From the time shrubs were planted in the lysimeters in 2017 to June 17 of 2018, all lysimeters were irrigated manually with tap water one to three times per week, depending on their water consumption. Total irrigation need was determined according to water level prior to irrigation and substrate porosity, with the aim of attaining a water level around 5 to 10 cm below the substrate surface after irrigation. This provided water saturated conditions for the plants, similar to conditions in a horizontal subsurface flow treatment wetland. The first contaminated irrigation took place on June 18, then two and three weeks after (July 2 and 11), and finally two times a week until September 7 for a total of 18 contaminated irrigation events. The amount of leachate provided during those irrigation events was fixed, and tap water was added, if necessary, to complete the total irrigation need. In the end, each lysimeter received 37L of leachate (raw or diluted according to the treatment) except for a few plants that had smaller irrigation needs at the end of the experiment; the contaminant charge applied for each treatment is detailed in Table 1.

A customized fertilizer solution with a nitrogen (N) concentration of 200 ppm and an NPK ratio of 21:7:14 was added to the irrigation water weekly until July 13, after which N concentration was raised to 400 ppm due to notable signs of N deficiency. A mite (*Tetranychus* sp.) infestation was detected in early July, and despite a careful pesticide application every 2 days (Trounce, NFS 176), the infestation caused significant leaf defoliation of several individuals and notable defoliation of neighbors, mainly in bloc 3 (Figure 1c).

4.2.2 Data collection

All sampling took place over 16 weeks (starting 4 weeks prior to the first leachate irrigation), from May 23 to September 7, 2018. By that date, the damage to shrubs from the mite infestation was so important that we were forced to terminate the experiment.

4.2.2.1 Plant measurements

Leaf area (LA), proportional growth rate (pRG), biomass production, evapotranspiration rate (ET; total quantity of water loss through ET over a given period of time), photosynthesis rate (Ps), instant transpiration (T; estimated transpiration rate at a specific sampling time) and stomatal conductance ($\bar{G}_s$) were measured. LA was calculated weekly based on direct counting of the number of leaves on each willow and the mean size of one leaf. Throughout the month of June, multiple leaves were randomly collected from the shrubs at different stem heights and development stages to estimate the mean area of one individual leaf using optical software (Mesurim Pro v3.4.4.0). pGR was also calculated once a week using the following equation:

$$pRG = \frac{(H_{t+1} - H_t)}{H_t} \qquad \text{(Eq. 1)}$$

Where H_t was the height of the longest stem at the previous measurement, and H_{t+1} the height of the highest stem on the day the measurement was made. Fresh root and stem biomass was collected and weighed at the end of the experiment after residual leaves were removed, and then oven dried at 75°C until constant weight. Leaf biomass could not be measured directly because the plants lost leaves throughout the season and it was impossible to associate the fallen leaves with a plant. Instead, we determined the average weight of one leaf and multiplied it by the number of leaves counted when the LA was maximal, which provided us with an estimate of the minimal amount of leaf biomass produced per plant. The method used to calculate ET rate is detailed in section 2.2.2. Ecophysiological parameters (Ps, T and $\bar{G}_s$) were recorded using a portable measuring instrument (Li-COR 6400XT, Biosciences). Measurements were made one day per week from 10:00 AM to 1:00 PM, and conditions in the leaf chamber of the Li-COR (humidity, temperature, light and CO_2 concentration) were set to match the ambient conditions at the sampling time. Once a week, foliar symptoms of pathology (*e.g.* chlorosis, necrotic spots) were carefully noted and quantified (0 for absence, 1 for weak signs, 2 for present signs, 3 for generalized signs) for every plant.

4.2.2.2 Evapotranspiration calculation

Before and after every irrigation event, water level in the lysimeters was recorded. The lysimeters were in a greenhouse, so they received no rainfall, and the lysimeters were closed, so no drainage occurred. ET was then calculated as follows:

$$ET = \frac{[\theta_a(L_{t-1} - L_t)]}{d(t-1)-t} \quad \text{(Eq. 2)}$$

Where ET represents the mean daily lysimeter evapotranspiration (mm/d), Θ_a the effective substrate porosity (unitless), L_t is the water level prior to irrigation (mm) on a given irrigation day, L_{t-1} the water level after irrigation (mm) on the previous irrigation day and $d_{(t-1)-t}$ the number of days between each irrigation events. We used effective (or wet) porosity instead of the theoretical substrate porosity that is measured on completely dry substrate, to avoid overestimating ET. Effective porosity was calculated as follows, every time water level was monitored and irrigation was performed:

$$\theta_a = \frac{I}{A(L_{t+1} - L_t)} \quad \text{(Eq. 3)}$$

Where I is the irrigation volume added (m^3), A is the lysimeter area (m^2), L_t is the water level prior to irrigation (m) and L_{t+1} the water level after irrigation (m).

4.2.2.3 Water, soil and plant tissue analysis

Every two weeks, hydrogen potential (pH), oxydo-reduction potential (ORP), conductivity (EC) and temperature (T) were measured in the first 15 cm of the substrate using a multiparameter probe (Hanna Instrument, HI98194-6, Smithfield, RI). While pH and ORP are useful to better interpret As and Cr speciation, we also wanted to see if salinity increase (correlated to EC) would be an issue. The substrate measurements were made by collecting a 40 ml composite sample for each treatment, dissolving it in 80 ml of distilled water, letting the particles settle and taking the measurement in the supernatant. Before adding contaminants to the system, the three different substrates (sand, organic and coco) were analyzed for background contamination by PCP and PCDD/F congeners using gas chromatography mass spectrometry (GC-MS), and for As, Cr and Cu by inductively coupled plasma mass spectrometry (ICP-MS).. At the very end of the experiment, the same contaminant analysis was performed on composite samples of the first 20 cm of substrate for the 5 treatments and the control to estimate accumulation (or depletion) of each contaminant in the root zone. To assemble each composite sample, 3 small cylinders of substrate were collected from the 3 lysimeters of each treatment, for a total of 9 sub-samples per treatment, and then mixed together before weighing the mass required for the analysis (30 g). This operation was repeated twice, to yield 2 replicates per treatment. We also performed contaminant analysis for the plant tissues (roots, stems and leaves) to see if any accumulation and/or translocation had occurred. Unfortunately, due to a manipulation error, leaves were not sampled for the control treatment (S0). Root samples were only rinsed with distilled water prior to analysis. All contaminant analyses were performed by an accredited laboratory and sampled according to their protocol (Maxxam Analytique, Montréal, Quebec) and with the lowest detection limit available (from 0.1 to 1.8 pg/g for PCDD/Fs congeners; 0.1 mg/kg for phenolic compounds; 0.5 mg/kg for As, Cr and Cu). Finally, translocation factor (TF) was calculated for the different contaminants by dividing the measured leaf concentration by the measured root concentration.

4.2.3 Data analysis

We used a type I ANOVA analysis to test the statistical influence of the treatments on plant physiological and morphological variables and on plant tissue accumulation of contaminants. Significant ANOVAs ($\alpha = 0.05$) were followed by a post-hoc Tukey's test to identify the different treatments. Because a mite infestation affected the third bloc of the experiment more severely, we also included the bloc number as a factor in the ANOVAs.. All statistical analyses were performed in R 3.5.1 software. We normalized LA, pGr, ET, Ps, T, and $\bar{G}_s$ results for S25, C25, O25, S50 and S100 treatments by dividing their average value by the average value observed for S0:

$$nX = \frac{\sum_i X_{trait}/i}{\sum_i X_{S0}/i} \quad \text{(Eq. 4)}$$

Where X represents a given parameter, X_{trait} the value of this parameter measured for a given treatment, X_{S0} the value of this parameter measured for the control treatment, and i the number of replicates. To help with the interpretation of the results regarding PCDDs congeners, they were associated with their relative octanol:water coefficient (log K_{ow}), which represents their hydrophobicity (Kim *et al.*, 2019).

4.3 Results

The leachate concentration had no significant effect on either variable, except for LA, which was significantly lower for the S50 treatment (Table 2). However, there was a bloc effect on LA and ET that was driven by bloc 3 according to the post-hoc analysis.

Nonetheless, some trends and the temporal variation of the parameters will still be discussed in the following sections. Interestingly, a similar trend was observed for ET, Ps, T, $\bar{G}_s$ and biomass, where mean values for the S25 treatment were higher than for S0, then decreasing gradually for S50 and S100 to values equal or inferior to S0. The substrate type significantly affected LA, ET and $\bar{G}_s$, and a bloc effect was noticeable only for LA (Table 2).

LA increased rapidly during the season and, at the beginning of contaminated irrigation on June 18, the average LA per willow was already 1.4 m^2. Maximal (or peak) LA was generally reached in late July or early August, ranging from 1.2 (S50, mite infestation source) to 5.1 (O25, bloc 1) m2 of leaves per tree. Mean LA was generally lower for the willows growing in sand, followed by those growing in coco fiber, and, finally, much higher in the organic substrate ($p < 0.001$; Table 2). LA for the different leachate concentrations showed a gradual decrease over time when compared to the control treatment (Figure 2).

The pGR of the stems was maximal in May, and decreased slowly over the growing season. Shrubs reached a maximal height of 3.2 m on average, and S0 and O25 were the treatments in which pGR was highest (Table 2). Although not significant according to the ANOVA analysis ($p = 0.61$), mean pRG for the different leachate concentrations showed a gradual decrease over time when compared to the control treatment, particularly after week 12 of the experiment (Figure 2).

Mean ET rate from May 3 to September 10 was 9.9 ± 4.9 mm/d, while ET of the unplanted lysimeter was 1.0 ± 0.7 mm/d on average, meaning that plant T accounted for about 90% of ET. Willow displayed a higher ET in the coco fiber substrate and even more in the organic substrate (p = 0.11; Table 2). Temporal variation of ET showed little difference between the different leachate concentrations, but willow irrigated with the 25% concentration generally had slightly higher ET rate than the control, and the contrary occurred for 50 and 100% concentrations (Figure 2). ET was also consistently higher in coco and organic substrate, but by week 12, ET in coco substrate started to decline and was equal to ET in sand by the end of the experiment. (Figure 2).

Ps, T and $\bar{G}_s$ mean values were the highest in O25 and lowest in S0 treatments, although neither leachate concentration nor substrate type seemed to have a significant effect on these variables (p = 0.93, 0.60 and 0.18 respectively; Table 2). Until the 10th week of the experiment, mean Ps rate was similar for all treatments (Figure 2). In the 11th week, Ps of the contaminated treatments increased in comparison to the control plants, and remained slightly higher until week 13. Inversely, in the last two weeks of the experiment, Ps of the contaminated treatments was much lower than Ps of the uncontaminated shrubs, except for O25 (Figure 2). Once contaminated irrigation began, T rate and $\bar{G}_s$ began to show more variability depending on the treatment, tending to increase in contaminated treatments (Figure 2). However, by the end of the experiment, mean values of those two parameters were similar to or lower than the control results.

Total dry biomass produced was 375 g per tree on average, and stems constituted 80% of total biomass. Biomass production was greater for shrubs growing in coco fiber and organic substrate (p = 0.22; Table 2). Some foliar symptoms, such as chlorosis and necrotic spots, were detected throughout the season, but were not very notable and did not seem to be related to the contamination, as they were equally present in control lysimeters and under the different leachate concentrations (data not shown). However, plants growing in the organic and coco fiber substrates showed important signs of nutrient deficiency, even after the fertilizer concentration was doubled. The leachate concentration did not affect soil pH, EC or ORP, which were, respectively and on average, 7.6 ± 0.5, 206 ± 131 µS/cm and 246 ± 32 mV. EC increased throughout the experiment, with an average value of 350 µS/cm at the last measurement, and was always higher in coco fiber and organic substrate compared to sand substrate.

Background contamination was observed in the substrate for all contaminants except As (Table 3). An increase in contaminant concentration at the end of the experiment was barely noticeable, and no phenolic compounds or As were detected either before or after the experiment (Table 3). As for the presence of contaminants in the plant tissues, PCDD/Fs and Cu were found in all tissues, while As and Cr were found in roots only, except for a small concentration of Cr detected in the leaves of the S100 treatment (Table 3). No As was found in the roots of the S25 and O25 treatments, and the accumulation in the roots of the control lysimeter (S0) was similar to that in the other treatments. For Cr, accumulation in the roots of the control was higher than in all other treatments. The highest concentrations of PCDD/Fs were found in the leaves, and Cu was more concentrated in the roots. The distribution of the congeners of PCDD/Fs measured in the different compartments of the lysimeters (Figure 3) shows that: 1) the proportion of a congener increased with the number of chlorine atoms, octa-chlorinated dibenzo-dioxin/furan (OcCDD/F) being the most present in the majority of the compartments, 2) the proportion of the different congeners in the substrates changed from the beginning (T0) to the end of the experiment (T1) and 3) *light* dioxin congeners such as Te/Pe/HeCDD were found in plant leaves, but not in stems or roots of the willow.

Based on biomass produced and concentration measured, we estimated that willow accumulated up to 0.07 mg of As (S0), 0.7 mg of Cr (S0) and 6 mg of Cu (O25) in their tissues (Figure 4). Since no contaminants were detected in leaves for PCP, As and Cr, no TF was calculated. TF for copper ranged from 0.6 for the S50 treatment to 1.7 for O25 treatment. For total PCDD/Fs, TF ranged from 14 (O25) to 87 (S100) and, for PCDDs, seemed correlated to congener hydrophobicity (log K_{ow}; Figure 5).

4.4 Discussion

Except for a certain LA inhibition, the different concentrations of leachate added to irrigation water had no clear phytotoxic effect on the willows. Furthermore, and although not statistically significant, the most diluted treatment (25%) tended to increase some physiological parameters. We can therefore suggest that *S. miyabeana* 'SX67' is tolerant to irrigation with a leachate contaminated with ACC and PCP under the concentrations tested in this study. At the end of the experiment, all contaminants could be found in/on the willow roots, but only Cu and PCDD/F were detected in aerial parts. The different types of substrate had different background contamination and were associated with significantly different results for most willow parameters measured.

4.4.1 Willow tolerance, uptake and translocation for PCP derived contaminants

In our samples, the concentration of all phenolic compounds measured, including polychlorinated ones derived from PCP, never exceeded 3.5 µg/L. *Salix* species have previously been found to demonstrate tolerance to a certain range of phenolic compounds; this tolerance decreased with the addition of Cl atoms (Clausen and Trapp, 2017). For example, a concentration of 200 mg/L of phenol was needed to observe a drastic decrease in photosynthetic activity in *S. babylonica* over three days (Li *et al*., 2015), while EC_{50} (*i.e.* concentrations inducing a negative effect in 50% of the organisms observed) of polychlorinated phenols were 5.8 to 37.3 mg/L for *S. viminalis* cuttings over 144 hours or less (Ucisik *et al*., 2007; Ucisik and Trapp, 2008; Clausen and Trapp, 2017; Trapp *et al*., 2000).

An average amount of 141 to 572 pg of PCDD/Fs, depending on the treatment, was provided to the willows, and the highest concentration of PCDD/Fs measured in the soil was 0.47 pg Toxic Equivalents (TEQ)/g (in the C25 treatment at the end of the experiment). To our knowledge, there is very little information on PCDD/Fs toxicity to plants, and even less for willows. However, Urbaniak *et al.* (2017) reported that the application of sewage sludge containing up to 6 pg TEQ/g of PCDD/Fs to a willow plantation (*S. viminalis*) had an overall beneficial effect on the plants, increasing LA, biomass production and chlorophyll content, while the same conditions proved to be phytotoxic for other plant species like *Sinapis alba* and *Sorghum saccharatum*. The authors explained such positive response by the high nutrient concentration in the sludge, combined with detoxification system of the plants (Urbaniak *et al*., 2017). Moreover, some studies that used PCDD/Fs concentration in plants as a biomonitoring tool reported very high concentrations of those contaminants in trees (up to 2.3x 10^5 pg/g of lipids) with no mention of notable tree mortality (Wagrowski and Hites, 2000; Wen *et al*., 2009). It is therefore no surprise that in the present study, *Salix miyabeana* 'SX67' proved to be tolerant to the raw leachate, because the concentrations of chlorinated phenolic compounds and hydrocarbons derived from the PCP were much lower than estimated phytotoxic concentrations. Concentrations of PCDD/Fs up to 1.4 pg TEQ/kg were found in the willow tissues at the end of the experiment. Concentration in the leaves was 3.4 times higher than in the roots on average, while stem concentration was about 21% of the root concentration. Organic pollutants, including dioxin and furan congeners, can accumulate in plant tissues via either soil or air (Zhang *et al*., 2017). For example, dioxins with 1 to 4 chlorine atoms are likely to volatilize in the air from water or soil and then be deposited on plant leaves or enter them through gas exchange (Bacci *et al*., 1992). PCDD/Fs being hydrophobic molecules, it is sometimes suggested that the major pathway for this contaminant accumulation in plant aerial parts is air-to-plant, because such molecules are not mobile in water and should be strongly bonded to organic matter in the soil (Bacci *et al*., 1992; Zhang *et al*., 2009). However, there is also clear evidence for root adsorption and absorption of PCDD/Fs in the soil, which can be explained by their relatively low molecular mass (below 1000 g) and high hydrophobicity (log K_{ow} from 6.8 to 8.2; Zhang *et al*., 2012). Yet, different species have shown different responses to PCDD/Fs (Zhang *et al*., 2009), and some plant families such as the *Cucurbitaceae* have even shown exceptionally high translocation of PCDD/Fs to aerial parts (Inui *et al*., 2011). Based on the analysis of the PCDD/Fs congeners presented in this study, we can state that *S. miyabeana* 'SX67' does accumulate PCDD/Fs, and even translocates them in its aerial tissues. Lighter PCDD/Fs (*e.g.* TeCDD and PeCDD) were found in greater quantities in the leaves than in the roots and stems. At this point, we should also mention that the calculated TF for PCDD/Fs were much higher than those reported in the literature (Inui *et al*, 2001; Nunes *et al*., 2014; Hanano *et al*., 2015), which raises the question of potential aerial deposition. However, while this would be more than plausible under field conditions, due to potentially contaminated rainfall, it seems unlikely that the ambient air in greenhouse contained a high concentration of gaseous PCDD/Fs given the low concentrations used, and the mulch layer and constant soil moisture that should have prevented the transport of aerial dust from the substrate. Furthermore, congeners with 5 or more chloride atoms are usually considered non volatile (Bacci *et al*., 1992). Theoretically, PCDD/Fs translocation factor should increase with the number of chloride atoms (which increase hydrophobicity or log K_{ow}; Zhang *et al.*, 2009; Bacci *et al.*, 1992). However, the inverse trend has been reported for PCDD/Fs hyperaccumulators, with TF decreasing with log K_{ow} increase (Inui *et al.*, 2001). We observed the same trend, but only for polychlorinated dibenzo-dioxin congeners with a log K_{ow} of 7.6 and higher (hxCDD to OcCDD).

4.4.2 Willow tolerance, uptake and translocation for CCA derived contaminants

In this study, the highest concentrations of As, Cr and Cu provided to willows were 0.53, 0.07 and 0.16 mg/L respectively, for a total of 14.4, 1.7 and 6.3 mg added in the S100 treatment. Considering that the lysimeter contained roughly 50 kg of soil, this represents a maximal soil concentration of 0.3, 0.035 and 0.13 mg/kg of As, Cr and Cu respectively. This explains why no As was found in the substrate (detection limit of 0.5 mg/kg), and suggests that willow was principally exposed to Cr and Cu from the substrate background concentration (7.3-14 to 5.6-10 mg/kg for Cr and Cu respectively). Although oxidation state of As was not directly measured, we can presume that the arsenite form (AsIII) should have been predominant according to the redox soil conditions (246 mV) and relatively high pH (7.6). However, there are other parameters influencing As speciation that were not monitored and this assumption should be taken with care. The ionic form of chromium was not measured either, but since most of the Cr naturally found in soil is trivalent (Barnhart, 1997), and the hexavalent state was only rarely detected on the industrial site where the leachate was collected (data not published), we can assume that most of the chromium measured in this study was in the Cr^{3+} form.

Tolerance of willows (EC_{50}) to arsenic has been reported to range from 3 to over 20 mg/L in lab tests of over 72 h (arsenate or As(V) form only; Clausen and Trapp, 2017). For *Salix purpurea*, Yanitch *et al.* (2017) reported a toxic effect from as little as 5 mg/L of As(V) in a hydroponic experiment, the effects increasing with increasing concentration of As. According to the Purdy and Smart study (2008), hybrids of *S. viminalis* x *S. miyabeana* and *S. sachalinensis* x *S. miyabeana* were the cultivars most tolerant to As contamination, with concentrations of As(V) as high as 18.7 mg/L having no effect on plant T and only a slightly deleterious effect on biomass production. In the present study, arsenic was detected in the willow roots only, and concentrations were below the detection limit in the roots of the S25 and O25 treatments. However, at higher As concentrations in water, it has been demonstrated that some willows can translocate As to aerial parts, that TF increases with increasing As concentration, and that the latter is further enhanced in the presence of phosphorus (Purdy and Smart, 2008). In the Purdy and Smart study (2008), *S. viminalis* x *S. miyabeana* was not only the most tolerant cultivar but also the most efficient As accumulator (up to 7000 mg/kg of As in roots, and 200 mg/kg in leaves).

As for chromium, Yu and Gu (2007) and Yu *et al.* (2008) tested the effect of an hydroponic solution of Cr^{3+} and Cr^{6+} (separately) on the T and metabolism of the hybrid *S. viminalis* x *S. alba*. Reduced T occurred at 15 and 4.2 mg/L of Cr^{3+} and Cr^{6+}

respectively, but none of the concentrations tested (up to 30 mg/L of Cr^{3+} and 12.6 mg/L of Cr^{6+}) had a significant effect on willow metabolism, apart from slightly reducing soluble protein content in leaves. In a field experiment, *Salix smithiana* was cultivated in soil contaminated with up to 140 mg/kg of chromium (along with significant concentrations of other heavy metals) without showing any visible signs of phytotoxicity (Kacálková *et al.*, 2014). However, most of the Cr in the soil was considered non-available according to a 0.11 mol/L acetic acid extraction method (Kacálková *et al.*, 2014); bioavailability of the contaminants was not determined in the present study. In a pot experiment, a soil Cr concentration of 70 mg/kg was found to have a relative phytotoxic effect on *Salix viminalis*, but *Salix* also proved to be the most tolerant of all the species tested (Ranieri and Gikas, 2014). Chromium was present in the substrate of all treatments, including S0, because of the substrate background concentration, and was consequently detected in the roots in all treatments. Root concentration of Cr was the highest for willows irrigated with tap water only (S0), and was significantly lower in the organic and coco fiber substrates. Cr was not detected in aerial parts, except for a small concentration in leaves of the S100 treatment. While Cr accumulation in willow roots has been reported to be high (up to 15 000 mg/kg; Yu and Gu, 2007), aerial TF seems to be quite low, ranging from 0.03 to 2 (Kacálková *et al.*, 2014; Ranieri and Gikas, 2014; Yu and Gu, 2007). However, TF is also thought to increase with initial Cr concentration (Yu and Gu, 2007), which could explain why Cr was detected only in leaves of the willow irrigated with the raw leachate. Chromium has a tendency to bind strongly with organic matter in soil (Fendorf, 1995; Balasoiu *et al.*, 2001), and this could explain the lower concentration of this element in willow grown in the organic and coco fiber substrates.

Other elements like iron also have the potential to immobilize Cr by forming highly stable complexes (Fendorf, 1995). We can therefore hypothesize that the chemical composition of the leachate could be responsible for the lower Cr accumulation in willow irrigated with the leachate compared to the control.

Finally, the concentration of copper in water, which ranged from 0.25 mg/L to 3.2 mg/L, was previously reported to be sufficient to decrease willow biomass production, although this depended greatly on the cultivar, and did not provoke other visible toxicity symptoms (Punshon *et al.*, 1995; Yang *et al.*, 2014). When considering the concentration of Cu in soil, willow could tolerate concentrations up to 455 mg/kg, again displaying a biomass decrease but no other toxic symptoms (Chen *et al*., 2012). Lastly, copper was found in all plant tissues, with higher concentrations in roots, followed by the leaves and then the stems, except for the O25 treatment, where Cu was more concentrated in aerial parts. Leaf and stem TF were respectively of 0.9 and 0.6 on average, which is higher than the TF reported by Yang *et al.* (2014) for 12 different willow cultivars. Contrary to a study by Chen *et al.* (2012), we did not find that increasing Cu concentration in soil increased willow Cu accumulation. However, in our experiment, only the C25 and O25 treatments provided significantly higher Cu soil concentration, and, at the same time, they provided conditions where Cu could be less mobile (*e.g.* complexion with high organic matter content).

For As, Cr and Cu, it would be expected that the substrate composition and concentration in molecules such as organic matter and other elements (*e.g.* Mn, Fe, Al) would strongly influence bioavailability of those contaminants to a plant (Girouard and Zagoury, 2009). However, based on the data collected in this study and similar examples from the literature, we can hypothesize that, even if a fair amount of the As, Cr and Cu present in the lysimeters at the end of the experiment was available to willows, none of those contaminants were concentrated enough to generate a phytotoxic response in the plant. Therefore, *S. miyabeana* represents a good candidate for treatment of CCA contaminated leachate.

4.4.3 Influence of the substrate

The two alternative substrates tested had an obvious positive impact on willow performance, and this effect was slightly more evident for the organic than the coco fiber substrate. Apart from the pGR, C25 and O25 treatment willows generally performed better in terms of ET, LA, Ps, T, $\bar{G}_s$ and biomass production. On the one hand, it is most probable that contaminants were less available in the two organic substrates because of their organic matter content, as discussed previously. On the other hand, leachate concentration in sand substrate had little impact on the plants, which suggests that contaminant availability might not be the main explanation for the better performance of C25 and O25. One of the possible causes of this increased performance is the nutrient sink initially present in this substrate compared to sand. However, this in turn increased the nutrient demand from willows, which resulted in signs of important nutrient deficiency throughout the experiment. This means that although the organic substrate initially benefitted the plants, it also increased the need for fertilization following plantation, which can represent substantial costs and manipulations, depending on the intended use of the willows. Root:shoot ratio was significantly decreased in the O25 and C25 treatments, due to higher stem biomass production rather than lower root biomass production. Furthermore, the O25 treatment showed even higher root biomass than S25 and C25, which could in turn increase resource prospection and phytoremediation potential. The willows growing in coco and organic substrate also used much greater quantities of water than those growing in sand, but we cannot confirm whether this is a direct effect of substrate physical properties or a correlated effect of biomass and LA increase. Nevertheless, this result represents an interesting optimization opportunity when using willow ET potential to reduce volumes of contaminated water.

4.5 Conclusion

Salix miyabeana proved to be tolerant to irrigation with a raw leachate contaminated with ACC and PCP. Based on the concentrations of all contaminants found in the leachate and previous tolerance studies, it is possible that this willow cultivar could sustain a much more concentrated leachate. Even at these low contaminant concentrations, willows have shown a capacity to accumulate all tested contaminants, and potential to translocate PCDD/Fs and Cu. Based on the literature and observed accumulation in roots, we can assume that translocation might have been observed as well for higher concentrations of As and Cr. Finally, the two types of organic substrate tested had significant positive effects on willow growth and physiology. Notably, we observed a change in willow reaction to contaminants that could be attributed to the substrate reducing phytotoxicity of the leachate. However, willow extraction potential was also reduced. This study is the first, to our knowledge, to investigate and evaluate *S. miyabeana* potential to remediate mixed wood preservative contamination in a complex system (mesocosms). Although the mesocosms were designed to mimic in situ conditions, it would be interesting to validate our findings in full-scale remediation systems (i.e. full-scale treatment wetland comprised of phytoremediation plantations). Future research should test the effect of this type of leachate in a longer term experiment and under more concentrated conditions, while investigating the actual availability of the contaminants for the plants after they have reacted with the substrate. Finally, more attention should be given to the risks associated with translocation of highly toxic compounds such as PCDD/Fs, which could be transferred through trophic networks.

Acknowledgments

This work was supported by the NSERC/Hydro-Québec Industrial Research Chair. Helpful comments on a previous version of the manuscript were provided by Karen Grislis. Our thanks to Hydro-Québec for their support and assistance, Benoît St-Georges for green house management and pesticide treatments, lab assistants for plant monitoring and data collection and lab colleagues for useful comments.

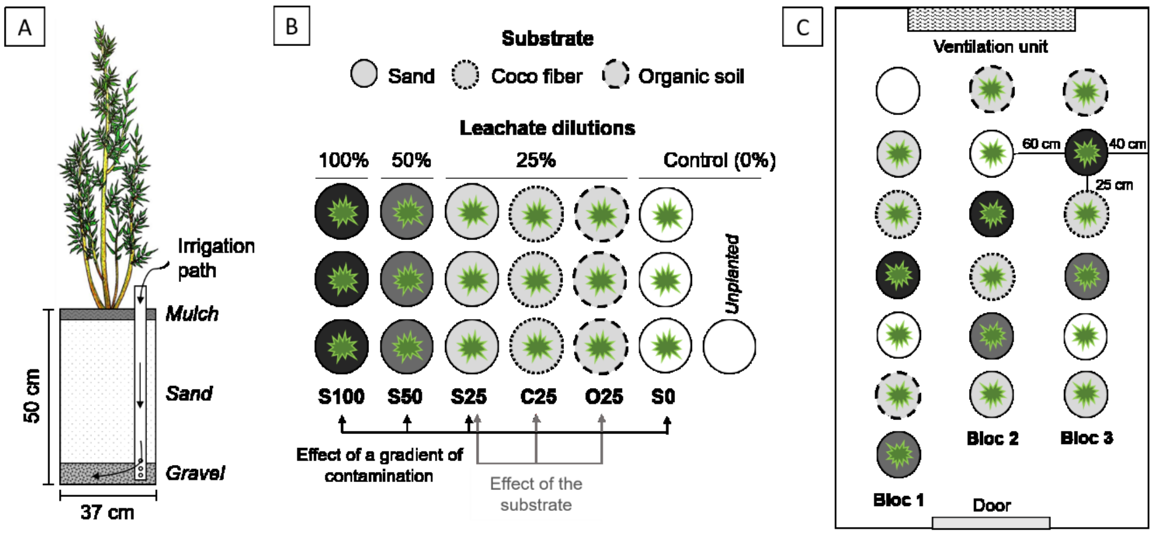

Fig 4.1 a. sectional view of the lysimeters showing the 3 different substrate layers and the subsurface irrigation path, b. experimental design, c. spatial arrangement of the 19 lysimeters

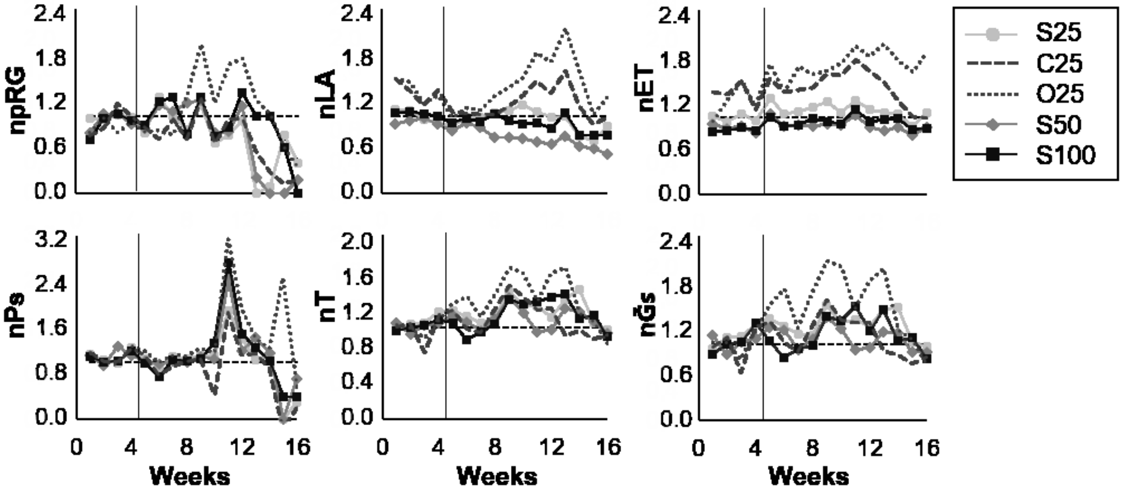

Fig 4.2 Weekly mean proportional growth rate (pRG), leaf area (LA), evapotranspiration rate (ET), photosynthesis rate (Ps), instant transpiration rate (T) and stomatal conductance ($\bar{G}_s$) of *S. miyabeana* 'SX67' irrigated with different concentrations of leachate (25, 50, 100) contaminated with wood preservatives (PCP and CCA), in different substrate (S, C, O) and normalized to the control (non-contaminated water, S0) observations. Horizontal dashed line represent no difference from the control. Vertical dashed line represent the beginning of contaminated irrigation after the fourth week.

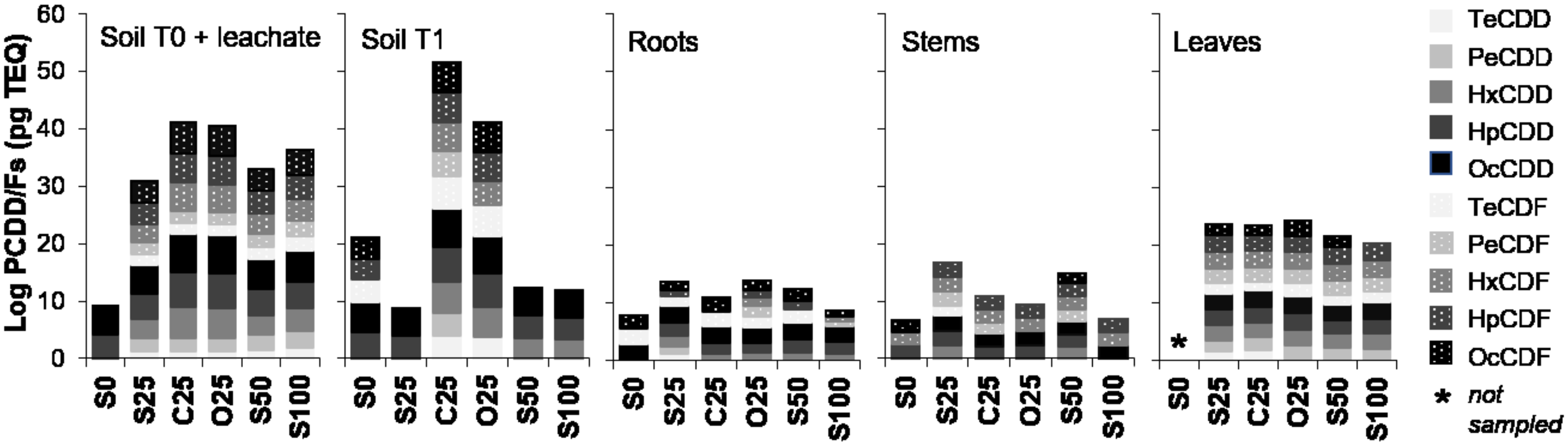

Fig 4.3 Log mass balance of the polychlorinated dibenzo-dioxin/furan congeners (PCDD/Fs) initially added to the mesocosms (Soil T0 + leachate), in the upper 20 cm of the substrate at the end of the experiment (Soil T1) and in the different tissues of *S. miyabeana* 'SX67' irrigated with different concentrations of leachate (0%, 25%, 50%, 100%) contaminated with wood preservatives (PCP and CCA), and in different substrates (sand, organic, coco fiber); Te = tetra, Pe = penta, Hx = hexa, Hp = hepta, Oc = octa.

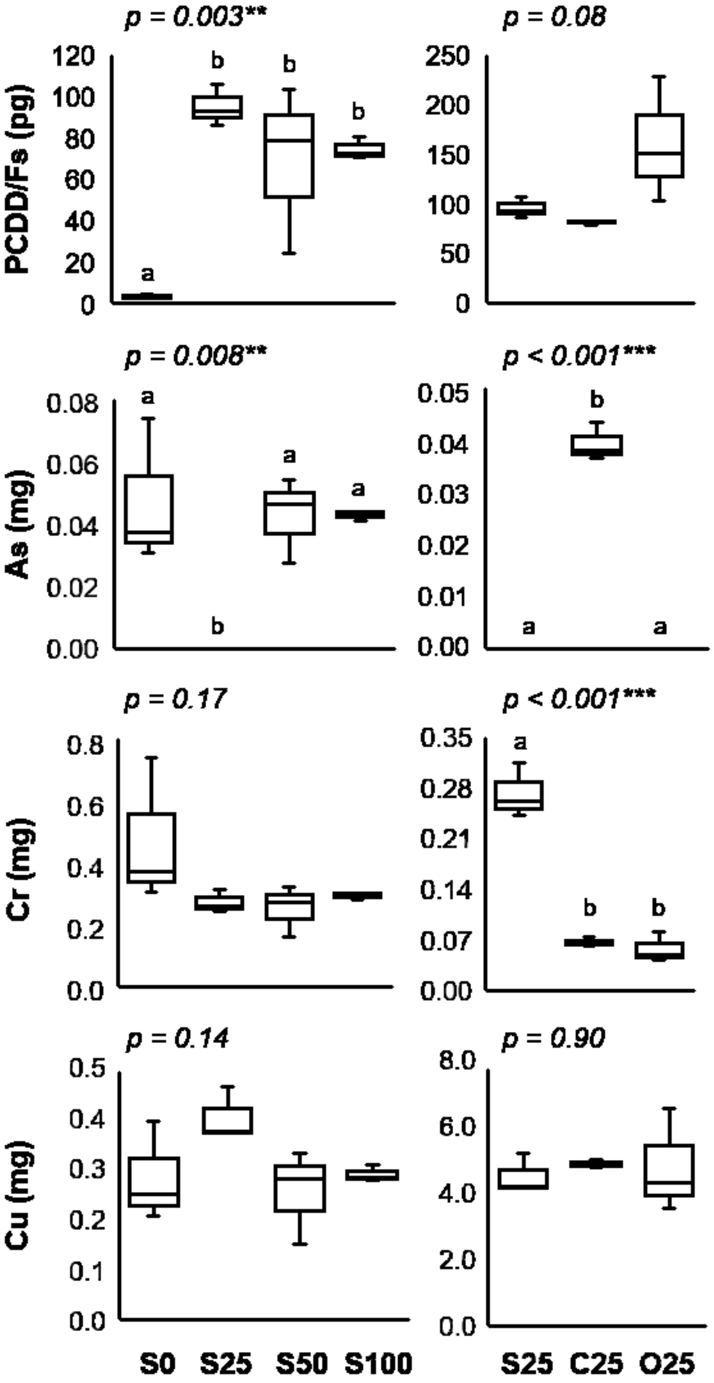

Fig 4.4 Total contaminant accumulation in *S. miyabeana* 'SX67' tissues after 12 weeks of irrigation with different concentrations of leachate (0%, 25%, 50%, 100%) contaminated with wood preservatives (PCP and CCA), and in different substrates (sand, organic, coco fiber)

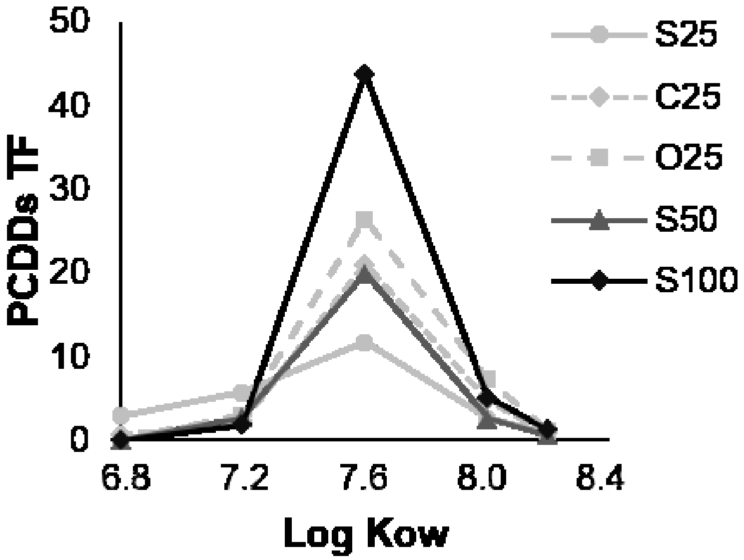

Fig 4.5 *Salix miyabeana* ‘SX67’ leaf translocation factor (TF) estimated for different polychlorinated dibenzo-dioxins congeners (PCDDs) and presented according to their octanol:water coefficient (log K_{ow})

Table 4.1 Contaminant concentration in the raw leachate and total mass added per treatment. TEQ = toxic equivalent; S25, C25 and O25 = sand, coco fiber and organic substrate with 25% leachate dilution, S50 = sand with 50% leachate dilution, S100 = sand with raw leachate (100%).

	Leachate concentration			**Total mass added per treatment**					
Contaminant	*Units*	***Batch 1***	***Batch 2***	*Units*	***S25***	***C25***	***O25***	***S50***	***S100***
PCP	µg/L	<1.0	<1.0	µg	-	-	-	-	-
3,5-DCP	µg/L	1.2	2.1	µg	14.9	15.3	15.3	27.1	60.4
PCDD/Fs	pg TEQ/L	5.0	27	pg TEQ	141	146	146	251	572
As	µg/L	260	530	mg	3.6	3.7	3.7	6.4	14.4
Cr	µg/L	24	68	mg	0.41	0.42	0.42	0.74	1.7
Cu	µg/L	180	160	mg	1.6	1.6	1.6	2.9	6.3

Table 4.2 Mean leaf area (LA), relative growth rate (RG), evapotranspiration rate (ET), photosynthesis rate (PS), instant transpiration rate (T) and stomatal conductance ($\bar{g}_s$), as well total dry biomass and root to shoot ratio (± standard deviation) of *S. miyabeana* 'SX67' over 12 weeks of irrigation with different concentrations of leachate contaminated with wood preservatives (PCP and CCA), in different substrates. Exponent letters represent the results of the type I ANOVA analysis, and the post-hoc Tukey analysis; different letters indicate a significant effect of the treatment (α = 0.05) and a capital letters indicate a significant bloc effect.

Willow parameter	**Leachate concentration**				**Substrate type**		
	0% (S0)	*25% (S25)*	*50% (S50)*	*100% (S100)*	*Sand (S25)*	*Coco (C25)*	*Organic (O25)*
Leaf area (m^2)	1.6^{A} ± 0.5	1.5^{A}± 0.3	1.1^{B} ± 0.5	1.4^{A} ± 0.1	1.5^{A} ± 0.3	1.9^{A,B} ± 0.2	2.3^{B} ± 0.7
Proportional growth rate (m/m)	0.08^{a} ± 0.02	0.06^{a} ± 0.01	0.06^{a} ± 0.01	0.07^{a} ± 0.01	0.06^{a} ± 0.01	0.06^{a} ± 0.01	0.08^{a} ± 0.01
ET rate (mm/d)	10.1^{A} ± 1.8	11.2^{A} ± 0.6	9.1^{A} ± 3.1	9.7^{A} ± 0.2	11.2^{a} ± 0.6	14.5^{b} ± 1.2	17.2^{b} ± 4.3
Photosynthesis (mmol CO_2 m^{-2} s^{-1})	5.3^{a} ± 0.9	5.6^{a} ± 0.1	6.0^{a} ± 0.5	5.6^{a} ± 0.3	5.6^{a} ± 0.1	5.0^{a} ± 0.3	6.5^{a} ± 0.1
Instant T rate (mmol H_2O m^{-2} s^{-1})	2.7^{a} ± 0.5	3.2^{a} ± 0.4	3.0^{a} ± 0.3	3.0^{a} ± 0.5	3.2^{a} ± 0.4	3.1^{a} ± 0.3	3.7^{a} ± 0.3
$\bar{G}_s$ (mmol m^{-2} s^{-1})	0.24^{a} ± 0.06	0.30^{a} ± 0.04	0.26^{a} ± 0.04	0.26^{a} ± 0.07	0.30^{a} ± 0.04	0.27^{a} ± 0.03	0.37^{b} ± 0.06
Total dry biomass (g)	333^{a} ± 98	366^{a} ± 51	267^{a} ± 81	318^{a} ± 29	366^{a} ± 51	444^{a} ± 10	524^{a} ± 160
Root:shoot ratio (g/g)	0.27^{a} ± 0.07	0.29^{a} ± 0.01	0.26^{a} ± 0.01	0.29^{a} ± 0.03	0.29^{a} ± 0.01	0.18^{a} ± 0.02	0.16^{a} ± 0.01

Table 4.3 Estimated contaminant mass in different substrates before (T0) and after (T1) 12 weeks of irrigation with different concentrations of leachate contaminated with wood preservatives (PCP and CCA), along with mass of the contaminants in the plant tissues at the end of the experiment. All results are based on dry weight of composite samples with 1 (plant tissues) or 2 (substrates T0 and T1) replicates. BDL = below detection limit (0.5 mg/kg).

		S0	**S25**	**C25**	**O25**	**S50**	**S100**
Soil T0	PCDD/Fs (pg TEQ/g)	0.0047	0.0047	0.28	0.26	0.0047	0.0047
	As (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL
	Cr (mg/kg)	7.3	7.3	14	10	7.3	7.3
	Cu (mg/kg)	5.6	5.6	10	10	5.6	5.6
Soil T1	PCDD/Fs (pg TEQ/g)	0.0079	0.0023	0.4350	0.2050	0.0016	0.0010
	As (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL
	Cr (mg/kg)	8.3	7.8	15	12.5	7.7	8.6
	Cu (mg/kg)	6.9	5.6	14	9.9	6.5	6.6
Roots	PCDD/Fs (pg TEQ/g)	0.0160	0.0240	0.0340	0.1000	0.0330	0.0150
	As (mg/kg)	0.65	BDL	0.53	BDL	0.76	0.61
	Cr (mg/kg)	6.5	3.3	1	.78	4.5	3.7
	Cu (mg/kg)	17	14	12	5.5	16	13
Stems	PCDD/Fs (pg TEQ/g)	0.0088	0.0530	0.0170	0.0010	0.0830	0.0010
	As (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL
	Cr (mg/kg)	BDL	BDL	BDL	BDL	BDL	BDL
	Cu (mg/kg)	6.3	8.1	7.0	6.5	6.1	6.0

Leaves	PCDD/Fs (pg TEQ)	*	1.2	0.8	1.4	1.2	1.3
	As (mg)	*	BDL	BDL	BDL	BDL	BDL
	Cr (mg)	*	BDL	BDL	BDL	BDL	0.63
	Cu (mg)	*	9.7	11	9.2	9.5	9.5

** Not sampled*

Chapitre 5 | Treating contaminated leachate with zero liquid discharge using an evapotranspiration willow bed: A modelling study

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Statut : In preparation for publication in *Ecological Engineering*

Abstract

The objective of our study was to propose a design approach for a zero liquid discharge (ZLD) system using an evapotranspiration willow bed (WB), applied to the treatment of leachate. One of the particularities of leachate treatment is that the volume of water to treat is entirely dependent on rainfall and is therefore very variable. Current design guidelines for zero discharge willow systems do not allow to design a very flexible system. Through hydrological modelling, we were able to propose a method for sizing the different compartments of a ZLD system that would be efficient (in terms of discharge), over a 20-year period. We tested our model in the specific case of a treated wood pole storage site were contaminated leachate is collected in an open tank of 2200 m^2 and 540 m^3 (Québec, Canada). During this period, annual precipitations ranged from 770 to 1300 mm and the system was not operated during the winter months (December to May). It appears that a WB area of 2100 m^2 and a total storage volume of 2600 m^3 would be sufficient to operate the treatment system without any liquid discharge. Designing a ZLD system, particularly in climate with high precipitations and extreme seasonal temperature variation, requires to include a large volume of storage to the system and to maximize evapotranspiration trough substrate selection, high fertilization and optimal water flux management. Despite that possible limitation, ZLD wetlands still represent a green technology that offers low maintenance and energy costs, concentration of contaminants or by-products, valorization of contaminants such as nitrogen or phosphorus through biomass production, and, most importantly, results in zero discharge to the environment.

Key-words: evapotranspiration wetland, zero discharge wetland, willow system, willow bed, phytotechnology, leachate treatment

5.1 Introduction

Rainfall leaching through various wastes (*e.g.* landfills, mine wastes, stored treated wood poles) generates every year large and variable volume of water that are required to be treated by the related industries. Among the available treatment solutions used for industrial wastewater treatment, some aim to reduce to zero the volume of water released into the environment and are referred to as zero-liquid discharge (ZLD) systems. Such systems were first developed to allow different industrial sectors to reduce their water consumption and reduce their treatment costs (Koppol *et al.*, 2004). It can also allow the industry to avoid having to obtain a discharge permit for its contaminated effluent. Because of the different constraints of wastewater treatment, the concept of ZLD can address various problems and is increasingly used (Tong and Elimelech, 2016).

Phytotechnology-based ZLD systems were introduced in the 1990s in the form of constructed wetlands planted with willows. They were used to treat domestic wastewater in Denmark and designed to generate zero effluent (Gregersen & Brix, 2001; Brix & Arias, 2005). Since then, Ireland has also used this technology (O'Hogain *et al.*, 2011; Curneen & Gill, 2016) and feasibility studies were successfully carried out in Mongolia (Khurelbaatar et al., 2017). This type of constructed wetland is now referred to as willow wetlands, willow beds or zero-discharge wetlands (Kadlec & Wallace, 2008; Dotro *et al.*, 2017). The targeted mechanism for reducing the volume of the effluent is evapotranspiration (ET) which represents the loss of water of a system by evaporation and by the transpiration of living organisms (*e.g.* plants). This natural process is sometimes used in environmental engineering, especially for the treatment of contaminated leachate (Białowiec *et al*., 2011). Using this green technology to treat industrial wastewater offers a number of advantages compared to conventional treatment options, including low maintenance and energy costs, concentration of contaminants or by-products in a confined compartment (*i.e.* the wetland substrate), valorization of contaminants such as nitrogen or phosphorus through biomass production, and zero discharge to the environment.

Willow systems for domestic wastewater treatment are typically designed based on hydraulic and surface loading rates based on population equivalent values (Dotro *et al*., 2017). A ZLD leachate treatment system should be designed to consider the flowrate that varies according to seasons, providing storage in winter and sufficiently irrigating plants during dry summer periods. Current design guidelines for willow systems are often based on rough estimations of ET (mean annual crop coefficient of 2.5 times a reference ET; Brix & Arias, 2005), which does not allow to design a flexible system.

The main objective of this study was to develop a design guideline for a leachate treating ZLD using an evapotranspiration willow bed. A modelling approach was used based on a detailed analysis of ET temporal variation and water flow management. This model was tested for a humid temperate continental climate of Southeastern Canada (Québec). This research provides a design basis for ZLD willow wetlands, suggests best management practices and provides a design tool to size ZLD treatment systems using a willow bed applied for leachate treatment.

5.2 Materials and method

5.2.1 Model description

5.2.1.1 Model development

The system design chosen for modelling comprised as a first compartment an open tank or pond (further referred to as an open collection tank; CT) that either stores wastewater or collect leachate under contaminated materials, and is therefore exposed to rainfalls (Figure 1). A primary treatment step has been included, here in the form of a treatment wetland (TW), and it is the effluent of the wetland that irrigates the evapotranspiration willow bed (WB; Figure 1). Finally, two equalization tanks (EqT1 and EqT2) are connected to the CT and the WB, respectively, to manage water inflow variability in the system. Although both EqT could have been combined in one, having them separated ensure that only pre-treated water enter the WB, thus increasing its life span, and allows to separate treated water from partially treated or raw wastewater. As illustrated in Figure 1, the only water input in the system is the rainfall occurring over CT, TW and WB and the output is through evaporation (E) and evapotranspiration (ET). The input water that is not instantly evapotranspirated moves from one compartment to the other and the closed circuit allows to operate the system with a ZLD. The model is developed to compute, on a daily basis, the value of every water flux and the volume of water contained in each component of the system after all water movements have occurred, based on the following hydrological balance equations :

$$CT = CT_{(t-1)} - Q_{oCT(t-1)} + \frac{A_{CT}}{1000}(P - E) - Q_{TW} + Q_{rCT} - Q_{wCT} \qquad \text{(Eq. 1)}$$

Where $CT_{(t-1)}$ represent the water volume in CT the day before (m^3), $Q_{oCT(t-1)}$ the overflow of the CT as calculated the day before (m^3), A_{CT} the surface area of the CT (m^2), P and E the rainfall and evaporation (mm), Q_{TW} the irrigation of the TW (m^3), Q_{rCT} the recirculation from EqT1 to the CT (m^3) and Q_{wCT} the water volume withdrawn from CT before wintering of the system (m^3).

$$TW = TW_{(t-1)} - Q_{oTW(t-1)} + \frac{A_{TW}}{1000}(P - ET_{TW}) + Q_{TW} - Q_{wTW} \qquad \text{(Eq. 2)}$$

Where $TW_{(t-1)}$ represent the water volume in TW the day before (m^3), $Q_{oTW(t-1)}$ the overflow of the TW as calculated the day before (m^3), A_{TW} the surface area of the TW (m^2), P and ET_{TW} the rainfall and evapotranspiration of the TW (mm), Q_{TW} the irrigation of the TW (m^3), and Q_{wTW} the water volume withdrawn from TW before wintering of the system (m^3).

$$WB = WB_{(t-1)} - Q_{oWB(t-1)} + \frac{A_{CT}}{1000}(P - ET_{WB}) + Q_{WB} + Q_{rWB} - Q_{wWB} \quad \text{(Eq. 3)}$$

Where $WB_{(t-1)}$ represent the water volume in WB the day before (m^3), $Q_{oWB(t-1)}$ the overflow of the WB as calculated the day before (m^3), A_{WB} the surface area of the WB (m^2), P and ET_{WB} the rainfall and evapotranspiration of the WB (mm), Q_{WB} the irrigation of the WB (m^3), Q_{rWB} the recirculation from EqT2 to the WB (m^3) and Q_{wWB} the water volume withdrawn from WB before wintering of the system (m^3).

$$EqT1 = EqT1_{(t-1)} + Q_{oCT(t-1)} - Q_{rCT} + Q_{wCT} + Q_{wTW} \qquad \text{(Eq. 4)}$$

Where $EqT1_{(t-1)}$ represent the water volume in EqT1 the day before (m^3), $Q_{oCT(t-1)}$ the overflow of the CT as calculated the day before (m^3), Q_{rCT} the recirculation from EqT1 to the CT (m^3) and Q_{wCT} and Q_{wTW} the water volume withdrawn from CT and TW before wintering of the system (m^3).

$$EqT2 = EqT2_{(t-1)} + Q_{oWB(t-1)} - Q_{rWB} + Q_{wWB} - Q_d \qquad \text{(Eq. 5)}$$

Where $EqT2_{(t-1)}$ represent the water volume in EqT2 the day before (m^3), $Q_{oWB(t-1)}$ the overflow of the WB as calculated the day before (m^3), Q_{rWB} the recirculation from EqT2 to the WB (m^3) and Q_{wWB} the water volume withdrawn from WB before wintering of the system (m^3).

Finally, in order to maintain a particular water flow in the system, a set of management rules were implemented in the model (Figure 2). Globally, these rules ensure that 1) water is always available for E and ET in both the CT and the WB and that sufficient water is available in the CT for irrigation of the TW at all time, 2) overflow of CT, TW and WB are conveyed to the right compartments, 3) the water level in CT, TW and WB is lowered before winter to prevent roots and pipes damage in TW and WB due to water freezing and to prevent spring overflow in CT, and 4) if, in ultimate remedy, water has to be pumped out of the system or discharged to the environment, it will be an effluent that has gone through both primary treatment in the regular treatment wetland and secondary treatment in the willow bed, and therefore contains the lowest concentration of contaminants possible.

5.2.1.2 Model parameterization and calibration

Based on the model design presented in Section 2.2.1, we can determine five categories of parameters that are needed for the model operation: component design, water flux management, plant parameters, evapotranspiration and meteorology (Table 1). Some of the parameters such as meteorological data are external and cannot be controlled, while auxiliary parameters, like component design, are determined by the user. Other parameters such as evapotranspiration are external, but can be modulated through management decisions (see *Design optimization opportunities*, Section 2.3). ET calculations are based on a previous study done on willow bed planted of Salix miyabeana ‘SX67’ (Frédette *et al.*, 2019a). Evaporation

(E) from the CT it estimated to be about 80% of the Penman-Monteith reference evapotranspiration (ET_0; Allen *et al.*, 1998), TWs evapotranspiration (ET_{TW}) is estimated to be equal to ET_0 (crop coefficient, or K_{et}, of 1) and WB evapotranspiration is calculated with equations determined by Frédette *et al.* (2019a) :

$$ET_{WB} = \bar{G}_s \cdot LAI_{act} \cdot (VPD/p) \qquad \text{(Eq. 6)}$$

Where ET_{WB} represents the evapotranspiration of the willow bed (mm/d), $\bar{G}s$ the general stomatal conductance of the WB (mm/d), LAI_{act} the leaf area index capable of transpiring (m^2/m^2), *VPD* vapor pressure deficit (kPa) and *p* sea level barometric pressure (101,325 kPa). $\bar{G}_s$ is calculated as follow:

$$\bar{G}_s = 0.0648HBS \cdot [42.4T^{0.5} + (-0.006DOY^2 + 2.7DOY) + (-0.0055R^2 + 0.2R) + 0.32RH - 170] \qquad \text{(Eq. 7)}$$

Where *0.0648HBS* represent the hours of effective sunlight (h/d) multiplied by the coefficient required to convert the result in mm/d units, *T* the mean daily temperature (°C), *DOY* the day of year, *R* the daily solar radiation (W/m^2) and *RH* the relative humidity (%). A meteorological database covering 20 years (1996 to 2015) and including all the necessary parameters was created with data provided by Environment and Climate Change Canada (ECCC, 2019).

5.2.1.3 Model validation

This modelling study uses data collected from a demonstration scale leachate treatment system, located in Québec, Canada and operated since 2012 as a reference. This system was built to evaluate the performance of different wetland processes to treat a pentachlorophenol (PCP) and chromated chromium arsenate (CCA) contaminated leachate. This system was not designed as a ZLD and its effluents is discharged to a municipal sewer. The treatment system consists of 1) a 2240 m^2 CT over which are stored wood poles treated with CCA and PCP, connected to 2) four parallel horizontal subsurface flow TWs of a combined area of 125 m^2, whose effluents are combined and conveyed to 3) a 48 m^2 WB for treatment polishing before final discharge to municipal sewer. The CT can store up to 540 m^3 of leachate and pumping of this leachate to the TWs take place only during warm months when there is no risk of freezing damage to pipes and when vegetation can grow. The average flowrate to the four TWs is 3 m^3 per day, but it can be adjusted according to the varying incoming flow. The total water holding capacity of the TWs and the WB is estimated at 53 m^3 and 24 m^3, respectively. The TWs overflow is continuously discharged to the WB of which the effluent is discharged to a municipal sewer. A more detailed description of the overall treatment system and of one of the four TWs can be found in Lévesque *et al.* (2017) while a detailed study of the WB can be found in Frédette *et al.* (2019a). Mean annual rainfall and temperature at the experimental site are 1000 mm and 6.8 °C, respectively. The site elevation is 91 m above sea level and the plant growing season is about 170 days. For the purpose of this study, the following parameters were monitored on the reference site during 2016, 2017 and 2018 operation seasons: the volume of water pumped into the TWs (aTW; m^3), the volume of both WB affluent and effluent (aWB and eWB; m^3) and the WB evapotranspiration (ET_{wb}; m^3). To validate our model, we slightly modified the conceptual model presented in Section 2.2.1 so that the overflow of the WB went out of the treatment system instead, and both equalization tank were removed, since there is currently none of them on site. We simulated only the operating seasons, which were from May 9 to November 30 in 2016 (206 days), from May 15 to November 9 in 2017 (179 days) and from May 10 to October 31 in 2018 (175 days).

Following the simulations, we were able to calculate aTW, aWB, eWB, ET_{wb}. Correlation of simulated and measured values allowed us to validate the model.

5.2.3 Design and management optimization

5.2.3.1 Determination of optimal coppicing cycle

Using a willow planted wetland implies that coppicing of the woody biomass is required on a 2 to 4 year coppicing cycle, as is often suggested for willow plantations for biomass production (Bullard *et al*., 2002). Coppicing is also essential to maintain a high plant activity, which is correlated to a high evapotranspiration rate (Dotro *et al*., 2017). Recently coppiced willows, however, have less leaf area available for transpiration compared to mature trees. To minimize the effect of coppicing on evapotranspiration, alternating coppicing in different sections of the willow bed has been suggested (Gregersen and Brix, 2001; *e.g.* one half of the bed coppiced one year and the other half coppiced on the second year, for a 2-year cycle). During 2016, 2017 and 2018, we measured $\bar{G}_s$ and LAI of the WB on the reference site. Willow shoots were 2 year old in 2016 and were cut back at the end of 2017 growing season, meaning that we can compare $\bar{G}_s$ (a proxy of the evapotranspiration rate) and LAI of one, two and three year old shoots. We then simulated the operation of the treatment system varying only the coppicing cycle (2 or 3 years) to see if one option should be preferred over another.

2.3.2 Evapotranspiration optimization

Although evapotranspiration in mainly driven by climate and plant physiological traits, providing favorable growing conditions can enhance plant transpiration. For willows particularly, one way of promoting ET is by providing a constant water supply (Frédette *et al*., 2019b). In this model, we fixed a threshold water level (15 cm below ground) under which additional irrigation is provided to the willow bed, to ensure that water availability to willows is maximal at all time.

Varying the aspect ratio (L:W, length over width) of the WB, for a given surface area, could also represent an optimization opportunity, by increasing ET per unit surface. The higher the aspect ratio, the longer the perimeter of the willow bed, with willows growing on the perimeter of the bed having a significantly higher LAI (up to 300% more) then the one growing in the center), which is directly correlated with ET (Frédette *et al.* 2019a). To test the effect of the L:W variation on sizing criteria, we simulated the operation of the treatment system using a regular shape (L:W = 1.5) and then an elongated shape (L:W = 10). The LAI was adjusted directly in the model according to the number of willows growing on the border (W_{border}) and in the center of the bed (W_{border}). The LAI, W_{border} and W_{border} calculation methods are described in Table 1.

Another way of enhancing willow ET is by increasing the supply of nutrients available for plant growth (*i.e.* fertilization). In two studies where only the fertilization amount varied between treatments, it was demonstrated that fertilized willow (*S. alba*) evapotranspirated 96% more water than unfertilized ones, and that increasing the level of fertilization could increase ET by another 51% (Guidi *et al*., 2008, Pistocchi *et al*., 2009). Considering that the ET model used was calibrated over slightly fertilized willows (Frédette *et al.*, 2019a), we applied an ET increase coefficient (αF) of 1.51 to simulate the effect of high fertilization on the sizing criteria.

Finally, we wanted to simulate the effect of different substrates: 1) a sand substrate, commonly used in constructed wetlands and providing good drainage and 2) an organic substrate that provides increased organic matter and water retention in the root zone but is more susceptible of compacting and clogging. In a mesocosm study, we reported that ET of willows grown in sand was about 77% of that grown in a coconut fiber substrate and about 65% of that grown in a highly organic potting substrate (Frédette *et al.* 2019c). The ET equations used in our model were calibrated for willows grown in a peat and sand substrate (Frédette *et al*., 2019a). Although a peat substrate can be compared to a coconut fiber substrate because they share similar physical properties, Bañón *et al.* (2009) reported a 23% increase of ET in peat versus coconut fiber. Therefore, in our model, we considered that the ET calculated according to Frédette *et al.* (2019a) method represented optimized ET in terms of substrate and an ET decrease coefficient (αS) of 0.65 was used to simulate the effect of using a sand substrate.

5.2.4 Simulation scenarios

5.2.4.1 Simulation plan and design optimization

We simulated a time frame of 20 years of operation, which we believe was sufficient to represent a wide range of meteorological variation, particularly rainfall. The first objective of the simulations was to determine design criteria for the WB and the EqTs, applied to the actual design of the reference site. Then, we performed simulations by including optimization parameters previously described in Section 2.3 (Figure 3a) and identified the best design. After all designs were simulated, the best design was determined according to, for the purpose of this study, the EtQ volume and WB area required (a smaller value being better). Finally, we simulated the operation of the system with the identified best design with different areas of leachate collection tank to determine a numerical relation between CT area, WB and EqT sizing criteria (Figure 3b), so that our model could be used for the simulation of other conditions.

5.2.4.2 Determination of sizing criteria

Sizing of the EqT was determined based on a method described in Metcalf & Eddy-AECOM (2014), by first calculating the cumulative net inflow (Q_{net}) of water throughout one year in the compartment related to this EqT (*i.e.* CT for EqT1, WB for EqT2) for the 20 years simulated. Q_{net} was calculated monthly according to equation 8 for CT and equation 9 for WB:

$$Q_{net(CT)} = P - E - Q_{TW} \qquad \text{(Eq. 8)}$$

$$Q_{net(WB)} = Q_{WB} + P - ET \qquad \text{(Eq. 9)}$$

where P represent the monthly cumulative rainfall (m^3), E and ET the monthly cumulative evaporation and evapotranspiration respectively (m^3), Q_{TW} the treatment wetland irrigation and Q_{WB} the influent of the willow bed (m^3). Then, maximal, mean and minimal values obtained over a 20-year simulation were plotted (Figure 4a). An average line derived from the mean curve was projected below the minimal and above the maximal curves. The difference between the points where the line touched the maximal and minimal curves (tangent points), respectively, represented the volume of EqT required to cope with annual variation of the net inflow (Figure 3a). We repeated such calculations for different CT and WB areas to establish a relationship between EqT1 and EqT2 volume. Figure 4b presents the results of EqT1 sizing according to CT area from 1000 to 10 000 m^2. After determining the initial EqT size by this method, the volume available in the related compartment was subtracted from the EqT volume and it was also decided to add a 10% buffer to add some safety to the system (Eq. 10 and Eq. 11).

$$EqT1 = 1.1(EqT1_i - Vmax_{CT}) \quad \text{(Eq. 10)}$$

$$EqT2 = 1.1[EqT2_i - (Vmax_{WB} - Vmin_{WB})] \quad \text{(Eq. 11)}$$

Where the 1.1 coefficient represents the 10% buffer addition and $EqTx_i$, the volume of EqT required (calculated based on the previously described method). The relationships obtained were then implemented in the model so that when changing the CT or WB area, the corresponding EqT volume required was automatically adjusted. Finally, and for every design tested, we sized the WB by increasing its area until the simulation results allowed to achieve a zero liquid discharge over a 20-year period of simulation.

5.3 Results

5.3.1 Model validation

Based on 2016, 2017 and 2018 meteorological data and design parameters of the reference site (Table 1), we were able to model several components of the hydrological balance of the reference site treatment system with a determination coefficient of 74% (Figure 5). Both the influent and the effluent of the willow bed tend to be overestimated by the model (25 and 37% respectively), which can result from an under estimation of ET_{TW} and ET_{WB}. ET_{WB} appeared to be slightly underestimated by the model (20%; Figure 5). We concluded that this issue describes an overall conservative model, slightly increasing the risk of over-dimensioning the system compartments. Because the treatment system modelled is intended to reduce the risk of discharge by overflow, we consider that a conservative model is appropriate and we considered the validation results as satisfying.

5.3.2 Determination of an optimal coppicing cycle

Based on LA measurements, we determined a predictive equation to calculate the leaf area of a single willow at any time of the year, according to the stool age and the position of the shrub in the wetland (Figure 6). LA throughout the growing season was best described by a quadratic function, particularly for stools of two years of age (r^2 = 0.91 to 0.93). One year stools attained maximal LA in late August while 2 and 3 years stools attained maximal LA in late and early July, respectively. Average LA typically increased with stool age. Inversely, average $\bar{G}_s$ decreased with stool age, average value being maximal for stools of one year and significantly lower for stool of 3 years (Figure 7). After simulating the operation of a hypothetical treatment system design for 20 years and varying only the coppicing rotation cycle, we concluded that a two-year cycle should be privileged because it allowed to discharge 300 m^3 less water per year, on average (Figure 8).

5.3.3 Overview of the reference period

A summary of meteorological data used for the 20-year simulations is presented in Figure 9. Average annual temperature and rainfall throughout this period were 7.4 °C and 987 mm, respectively. Such temperature is slightly higher than average values provided for the same location over the years 1971 to 2000 (6.2 °C, ECCC, 2019), but rainfalls are similar to what would be expected (979 mm; ECCC 2019). The driest year was in 2001, with only 769 mm of rainfall, and the wettest year, in 2006, with 1 340 mm of rainfall. Annual cumulative ET_0 was 1075 mm on average, ranging from 875 mm in 2002 to 1240 mm in 1998.

5.3.4 Determination of sizing criteria

For the first simulations where the CT area was fixed at 2240 m^2, we found that a volume of 1910 m^3 was required for EqT1. Then, for each WB design tested, we were able to establish a linear relationship between the area of the WB and the volume of EqT2 needed (Table 2). It appeared that *1.3SaLf* and *10Salf* designs did not allow to achieve a zero liquid discharge objective, with a significant overflow volume generated most years of the simulations (Table 2). Total 20-year overflow systematically increased as the WB surface increased. A very small WB for these two designs led to the lowest overflows (Table 2). Very similar results for the two designs indicates that varying only the aspect ratio of the WB does not influence significantly the results. Intermediate designs optimized either for substrate, fertilization or both performed in the following order in terms of area required : *10OrLf* > *10SaHf* > *1.3SaHf* > *1.3OrLf,* A_{WB} ranging from 4000 to 5230 m^2. However, designs using organic substrate (*1.3OrLf* and *10OrLf*) required much less volumes of EqT2 (2 730 m^3 in average) than designs using a sand substrate (*1.3SaLf* and *10SaLf* ; 4 460 m^3). Finally, the two designs using organic substrate with high fertilization (*1.3OrHf* and *10OrHf*) led to the most promising results, with only 1360 m^2 WB and 1320 m^3 EtQ2 required to operate the system with ZLD. Again, for these two designs, increasing the aspect ratio did not lead to a major optimization of the results. Nevertheless, based on results presented in Table 2, the fully optimized design (*10OrHf*) can be considered the best performing design as it required the smallest WB area. Following the course of water through the system compartment of the best design throughout the years of the simulations can lead to several observations (Figure 10). First, we can see that water volume in the willow bed during the summers of 1996, 2001, 2002 and 2003 cannot be maintained at a minimal level because both the EqT were emptied during the previous years. It is then possible to think that additional manual irrigation of the wetland would have been necessary for these years. We can also observe that the maximal volume of EqT1 is never reached during the 20-year simulation and could probably be reduced by about 500 m^3. Finally, it seems that even if the CT is completely emptied during the summer months, the volume of this compartment is not sufficient to accumulate the cumulative rainfall of late Autumn, Winter and Spring. Increasing the depth of the tank, without changing its surface area, could help prevent off-season overflow of the CT, and further reduce the volume of EqT1 required. When looking at the relationship between the CT area and the WB area required to achieve a ZLD, it seems that a WB about two times larger than the CT would generally be sufficient when CT area in under 5000 m^2; this 2:1 ratio tend to decrease when area of CT increase further (Figure 11).

5.4 Discussion

The model was able to predict water flows in a treatment system with satisfactory results. Based of parameters of the reference site, we were able to establish a numerical relation between the area of an open collection tank and the surface area of willow bed required to conceive a ZLD system. Measurements of ET related plant parameters ($\bar{G}_s$ and LAI) at the reference site highlighted that while stool age increases, $\bar{G}_s$ decreases, mean LAI increases and maximal LAI is attained earlier in the season. Including this temporal variation in ET calculations lead to results suggesting that a 2-year coppicing cycle should be preferred over a 3-year cycle in order to maintain maximal ET. Simulations of the model according to the design of the reference site over a 20-year period showed that ZLD is feasible only if ET is maximized by the type of substrate and/or a high fertilisation level. Combination of optimal substrate and high fertilization provides the most promising sizing results. However, increasing the aspect ratio of the wetland did not lead to significant optimization of the system.

The hydrological model presented here shows that the volume required for water storage might be the most limiting aspect of this technology. While this aspect highlights the importance of considering ET and rainfall variability over time, some nuances should be pointed out. For example, in our study, sizing of EqT1 was based on the actual dimension of the CT of the reference site (2240 m^2, 543 m^3). Building a collection tank or pond with a greater volume (i.e. increasing the depth) should reduce substantially the need of storage volume to equalize this compartment, while also preventing Spring overflow. As discussed in section 2.1.1, both EqT could also be combined in one EqT for the whole system, which would reduce significantly the volume of storage required. This option, however, imply that it might be more difficult to discharge occasional volume from that tank because treated water is mixed with raw wastewater. Finally, storage volume needs should be much less important in locations with dryer climate and/or less annual temperature variation.

Our results, along with previous literature, confirm the pertinence of using willows in phytotechnology based ZLD systems. Salix species have shown a general tendency to increase ET when water supply are non limiting (Frédette *et al.*, 2019b), and their suitability for coppicing ensure that plants growth and ET rates are maximized. However, willows are not fitted for every region of the world. They are naturally distributed mainly in the northern hemisphere (Argus, 1986) and are considered invasive species in some southern locations like Australia, South Africa, and Argentina (Stokes, 2008; Henderson, Serra e*t al.*, 2013). Therefore, it would be interesting to expand future research on substitute species that would be adapted to other climates. Another issue of using willows for large ZLD installations is that large constructed wetlands planted with woody species like willow have to be designed to allow coppicing to be technically feasible. A possible solution would be to design a series of willows strips which, combined, would provide the required wetland area, while allowing machinery to circulate on the soil between the strips. At the same time, this would provide an aspect ratio optimization, therefore increasing ET per surface area of wetland. It would then require less substrate, but would require more lining membranes and a more complex irrigation system. Finally, there is also the issue of the biomass valorization: if willows or other woody species are to be used in ZLD system, there should be available option for valorization of the biomass produced (e.g. using fragmented stems as mulch in other locations, biofuel production). Possible translocation of contaminants to aerial parts of the willows should also be tested and considered before biomass valorization.

Another important aspect of any ZLD treatment system that was not tested *per se* in our model, was the accumulation of contaminant and/or salt in the system, as well as the fate of those contaminants and their effect on plant health. In the specific case of the reference site presented here, treatment efficacy of the TWs was generally high (Levesque *et al.*, 2017), and after 7 years of operation, the trees in the WB did not show any phytotoxic symptoms (Frédette *et al.*, 2019a). Furthermore, the cultivar used in this WB (*S. miyabeana* 'SX67') appear to be tolerant to the raw leachate produced on site (Frédette *et al.*, 2019c). We could therefore suggest with confidence that the life spawn of the WB, in this case, exceed 10 years. In a ZLD system with WB, the ET wetland is sized based water volume, and not contaminant charges, as is it the case for a treatment wetland (Kadlec and Wallace, 2008). Therefore, chances are that the ET wetland will be well over-sized in terms of treatment capacity, and life span of the wetland should then exceed, or at least equal, typical life spawn of treatment wetlands (40-50 years, Kadlec and Wallace, 2008). However, pre-treatment of the waste water, by TW or any other technology, should be favored, to ensure maximal life span of the WB. The technology used for pre-treatment should be selected according to the nature of the wastewater to treat, with consideration of occasional disposal of the contaminants accumulated in the treatment step. Ultimately, when a WB bed attains its maximal life span, the substrate should be removed and treated as recommended in the given location and given the contaminant concentrations.

5.5 Conclusion

Our results suggest that ZLD of a leachate treatment system using an evaporation WB is feasible in a humid climate with extreme seasonal temperature variation (South eastern Canada), although it requires large volume of water storage. The type of substrate used for the WB and the amount of fertilizer applied need to be taken into consideration for correct sizing of the system compartments. A 2-year coppicing cycle meaning that every year, one half of the willows are cut back, should be used to maintain maximal ET rate. The 20-year simulation of the system highlights the importance of designing a flexible system when treating leachate or other wastewater generated by rainfalls. Modelling temporal variation of both climate and ET is essential to achieve such flexible design. Although the operation of WB is relatively simple compared to other ZLD technologies, water flux in the system as to be carefully monitored and managed to ensure maximal ET and avoid overflows. ZLD systems using WB propose a solution for some actual limits of the typical ZLD treatment systems such as very high operational and energetic cost, and the difficulty to treat recalcitrant organic molecules (Tong & Elimelech, 2016). Future research could focus on testing the full-scale application of such a system based on the design approach presented here, including contaminant dynamic modelling in the design process, producing life-cycle analysis and investigating for substitute species.

Acknowledgments

This work was supported by the NSERC/Hydro-Québec Industrial Research Chair.

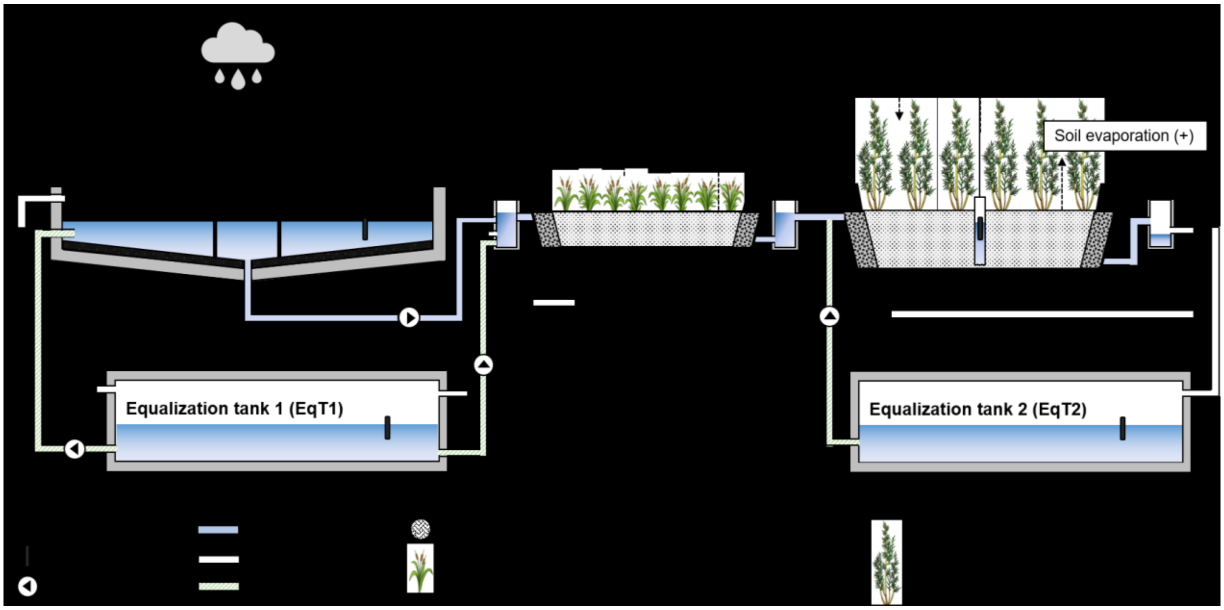

Figure 5.1 Design used to model the full operation of a zero liquid discharge leachate treatment system using an evapotranspiration willow bed. The drawing is not to scale. Water input to the system is exclusively through rainfall on the system compartments, and water output is through evaporation and evapotranspiration. Pumping or discharge of water is also available from the second equalization tank.

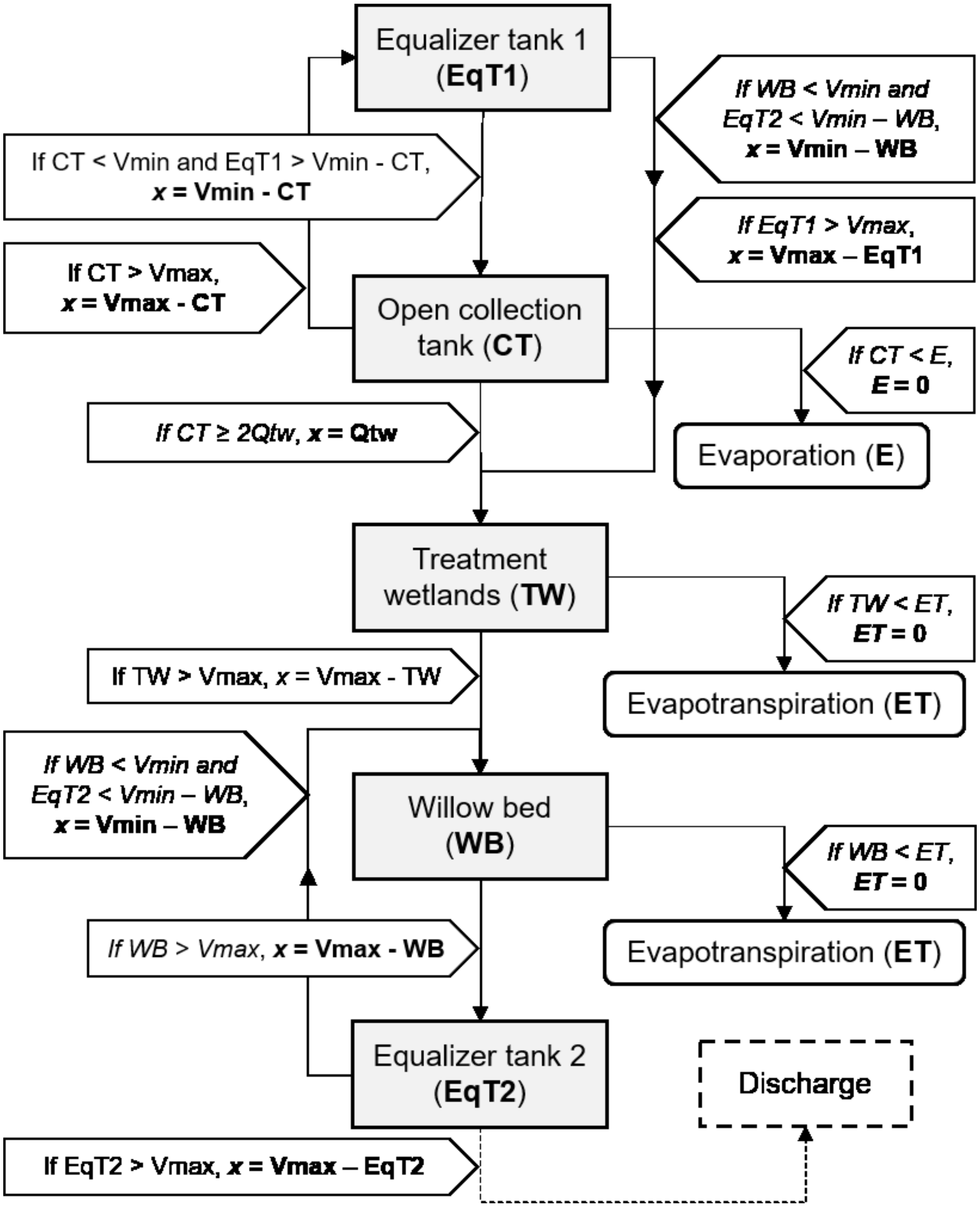

Figure 5.2 Management rules for water flow proposed for the operation of a ZLD leachate treatment system using a willow bed.

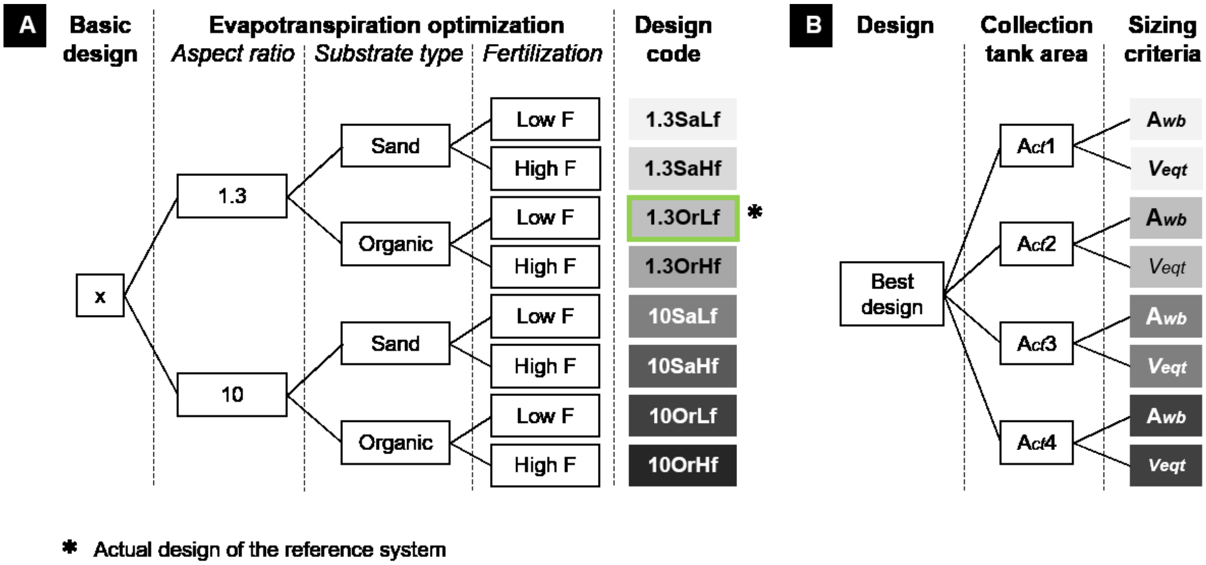

Figure 5.3 A. Simulation plan used to model the operation of a ZLD treatment system using an evapotranspiration willow bed and determine the best design. **B.** Simulation plan used to establish a relationship between the area of an open leachate collection tank and the willow bed area required to achieve a ZLD.

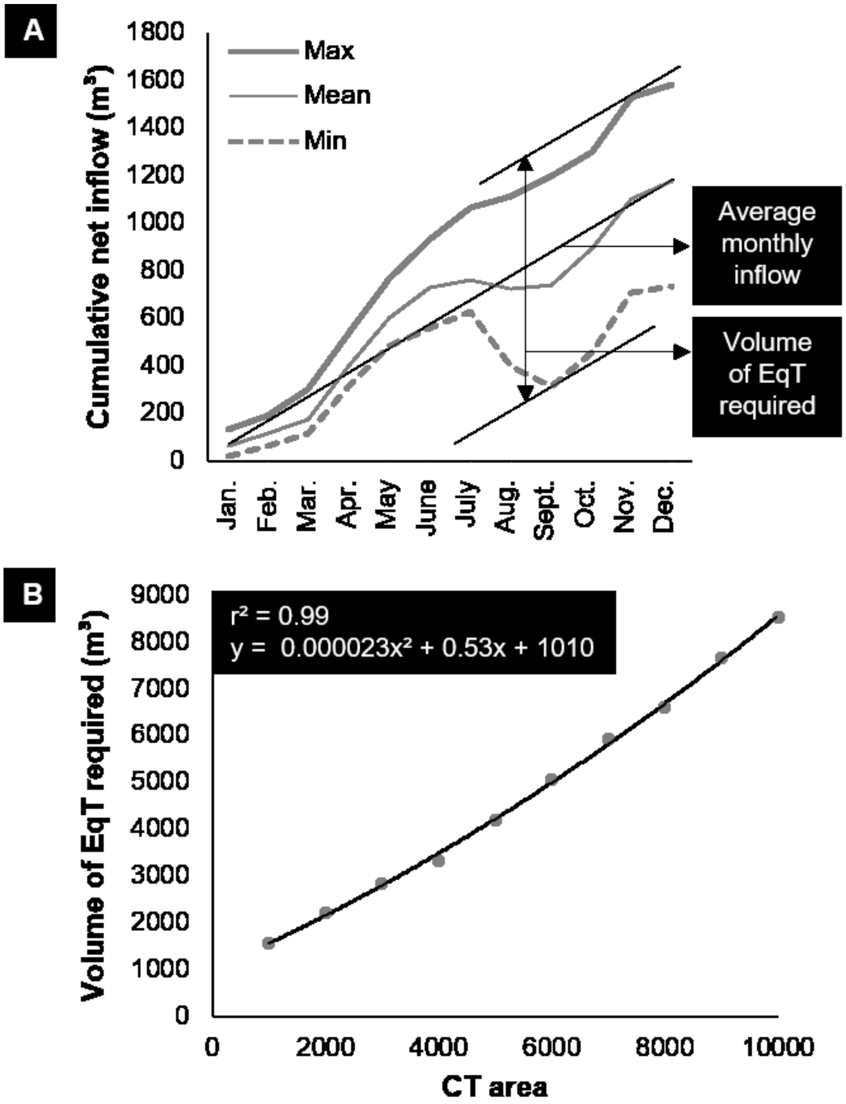

Figure 5.4 A. Graphical illustration of the methodology used to determine the volume of equalization tank (EqT) required. The annual trend of the cumulative monthly net inflow, presented here for a 1170 m² willow bed, represents the compartment influent (the overflow of the treatment wetland in the case of the willow bed) plus rainfall minus evapotranspiration. Minimal, mean and maximal monthly cumulative values are calculated from a 20-year climatic reference data set (1996-2015) for the region of Montreal, Canada. **B.** Relationship established between the leachate collection tank (CT) area and the volume of EqT required to equalize the inflow of this compartment and implemented in the model to calculate V_{EqT1}.

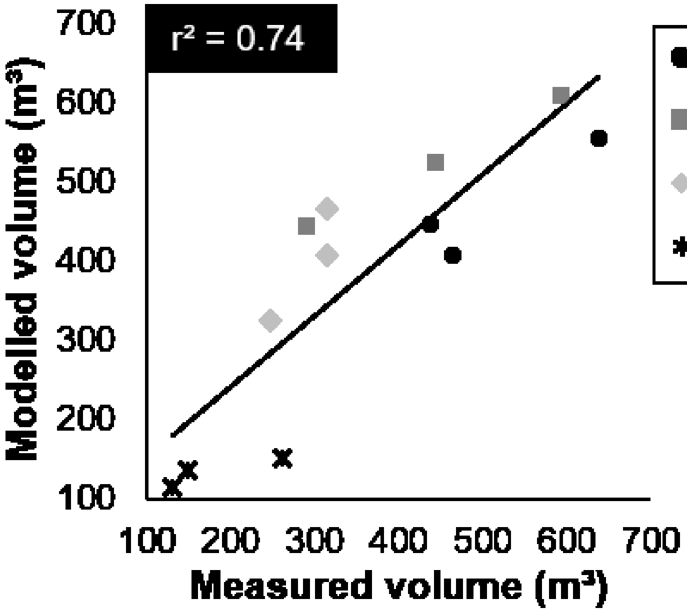

Figure 5.5 Comparison of modelled and measured values of some components of the hydrological cycle of a water treatment system using a treatment wetland and a willow bed. aTW = treatment wetland affluent, aWB = willow bed affluent, eWB = willow bed effluent, ETwb = evapotranspiration of the willow bed.

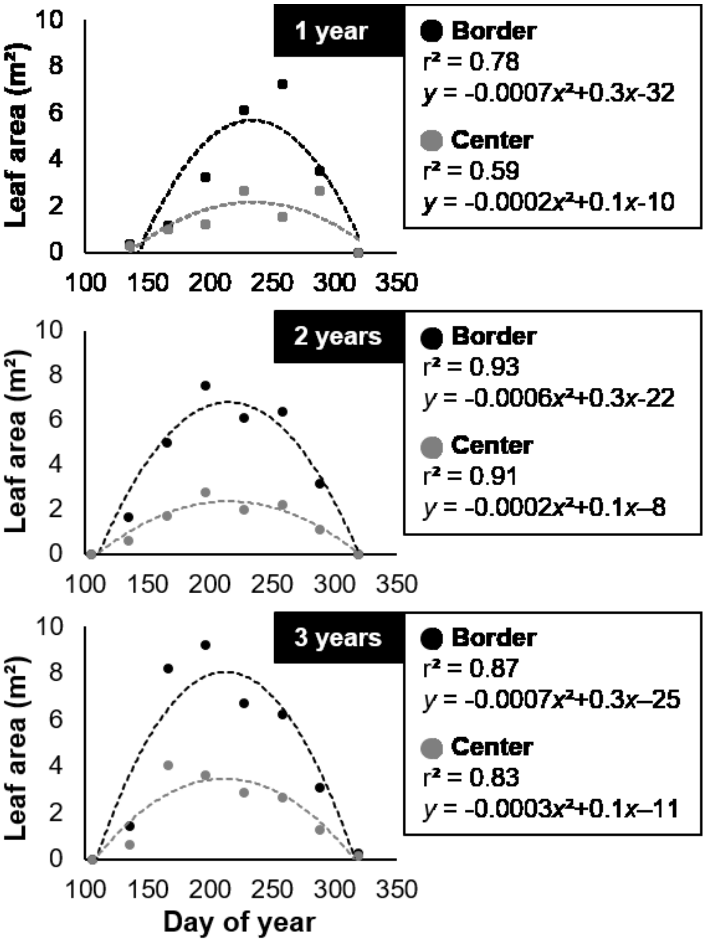

Figure 5.6 Mean leaf area per individual willow, according to stool age, position in the wetland and time of year.

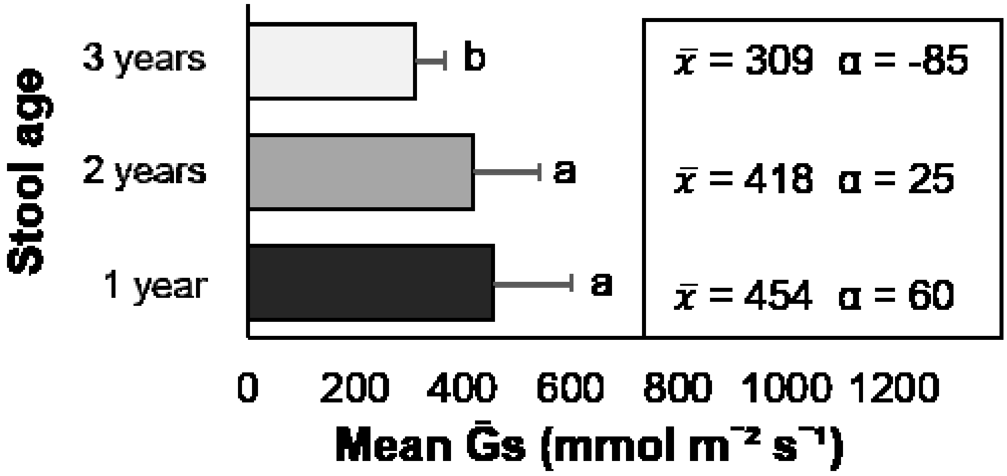

Figure 5.7 Mean stomatal conductance ($\bar{G}_s$) of *S. miyabeana* grown in treatment wetlands and according to stool age. Different letters at the end of the bars represent statistically different values. Average ($\bar{x}$) annual values of each year and its deviation from the 3 years mean value (α) are presented.

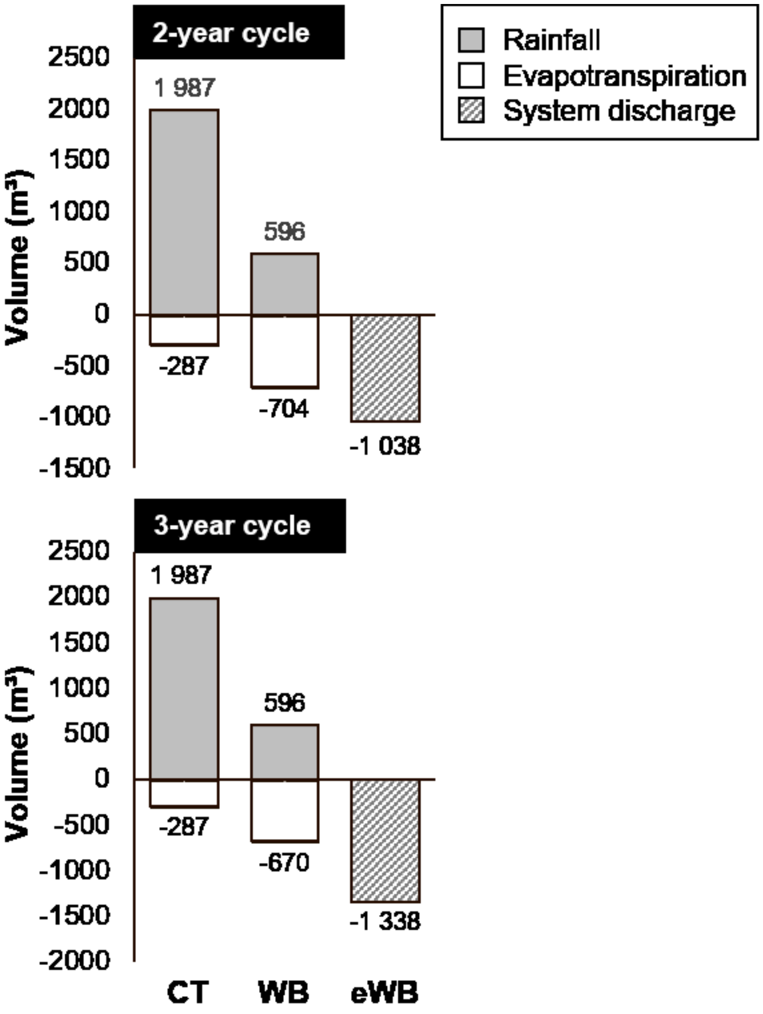

Figure 5.8 Modelled a**verage yearly** water balance of a hypothetical water treatment system using an evapotranspiration willow bed, according to the willows coppicing cycle selected. CT = collection tank, WB = willow bed, eWB = effluent of the willow bed.

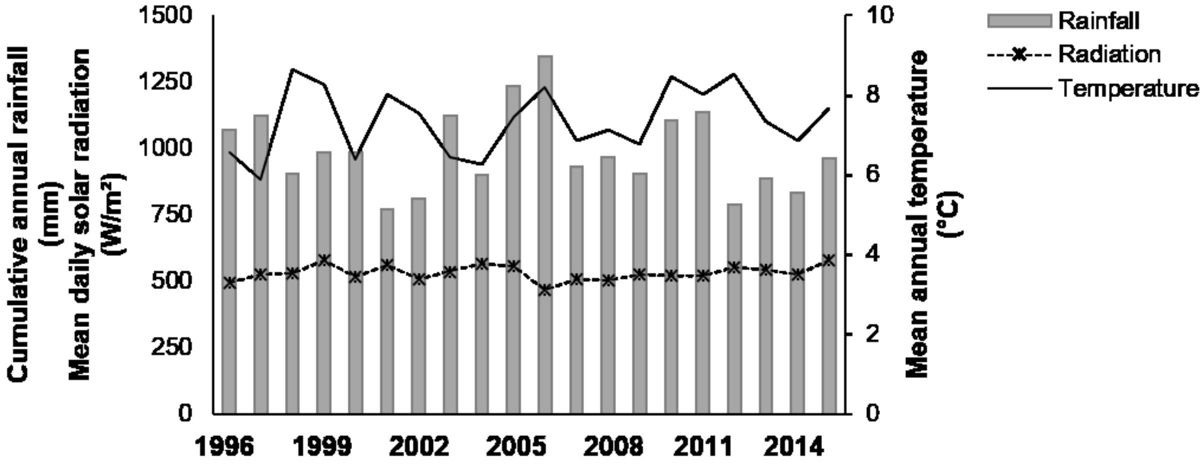

Figure 5.9 Overview of meteorological data at the YUL international airport, Montreal, Canada, during the 20 years during which they were used to simulate the operation of a ZLD treatment system using an evapotranspiration willow bed.

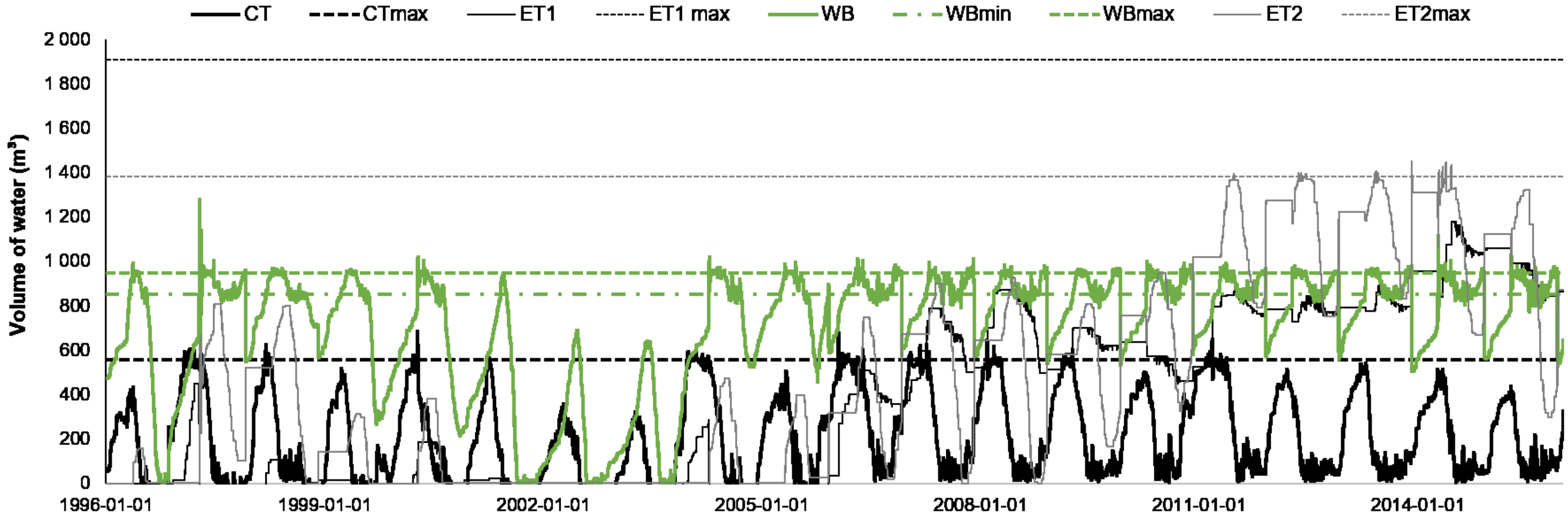

Figure 5.10 Daily variation, simulated for 20 years of operation, of the water volume in the different compartments of a ZLD treatment system using an evapotranspiration willow bed as a tertiary treatment. The volume of water in the upstream secondary treatment wetland is not shown.

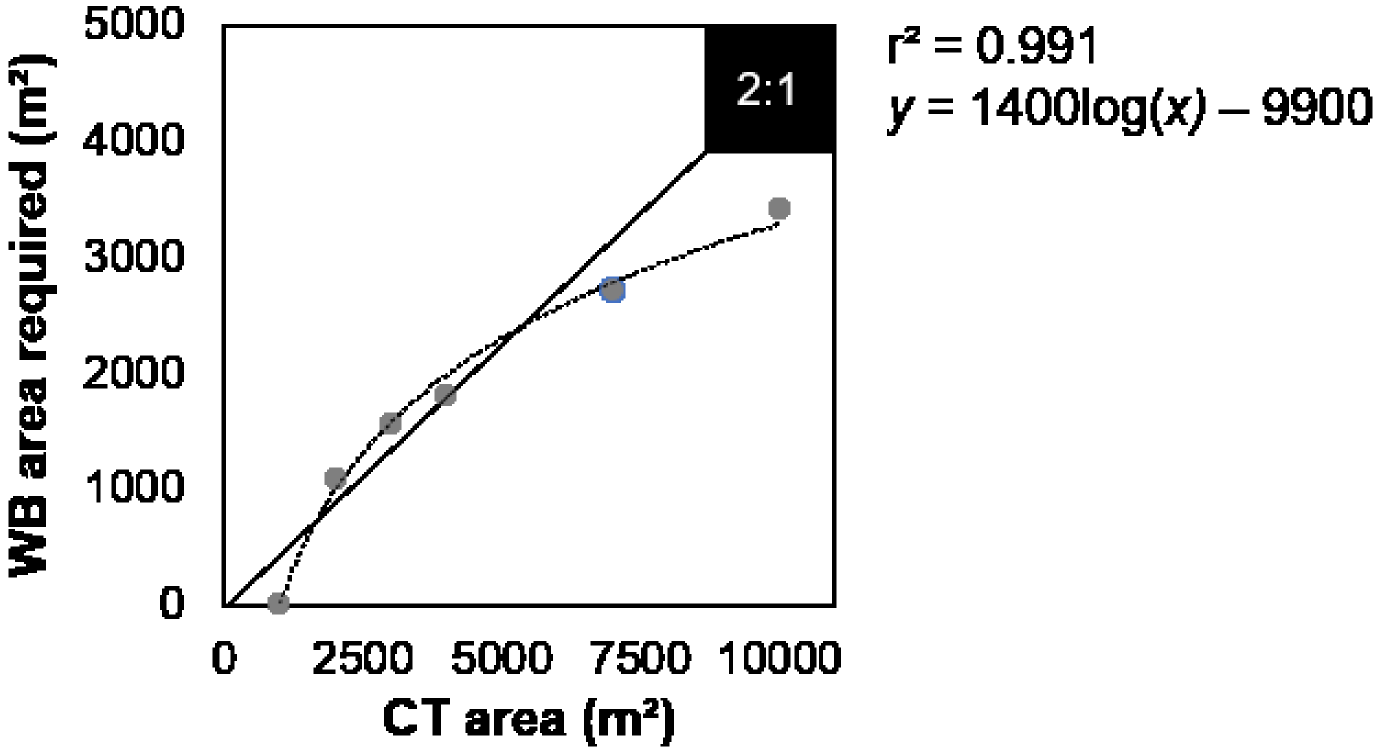

Figure 5.11 Relationship between the leachate collecting tank area and the willow bed area required to achieve a zero-liquid discharge effluent.

Table 5.1 Parameters used to model the operation of a ZLD leachate treatment system using an evapotranspiration willow bed. R_{value} represents the value of the parameter according to the actual reference treatment system design. External parameters are stochastic while auxiliary parameters are determined by the user during system design. Compart. = compartment of the system for which the parameter is needed, Ext = external, Aux = auxiliary.

Category	**Parameter**	**Units**	**Description**	**Compart.**	**Type**	**Equation/value**	$\mathbf{R_{value}}$
Compartments design	A	m^2	surface area	CT, TW, WB	Aux	-	48
	h	m	height (or depth)	TW, WB	Aux	-	1.5
	V_{max}	m^3	maximal water holding capacity	CT, TW, WB, EqT	Aux	for TW and WB: $\mathrm{V_{max}} = \mathrm{A} \cdot \mathrm{h} \cdot \theta$	28.8
	V_{winter}	m^3	Water volume remaining in the compartments after wintering (i.e. closing) of the system	CT, TW, WB	Aux	For CT and TW: $V_{winter} = 0.5 \cdot V_{max}$ For WB: $V_{winter} = 0.6 \cdot V_{max}$	
	V_{min}	m^3	Minimal volume of water that should remain in the compartment for optimized	CT, WB	Aux	for CT: $\mathrm{V_{min}} = 2 \cdot Q_{TW}$ for WB: $\mathrm{V_{min}} = 0.9 \cdot V_{max}$	-

			operation				
	V_i	m^3	Initial volume of water in the compartments at the beginning of the simulation	CT, TW, WB, EqT	Aux	For CT: $V_i = 0.9 \cdot V_{max}$ For TW and WB: $V_i = 0.5 \cdot V_{max}$ For EqT1 and EqT2: 0	-
	Θ	%	Substrate porosity	TW, WB	Aux	-	0.5
	L	m	Length	WB	Aux	-	8
	W	m	Width	WB	Aux	-	6
	L:W	-	Aspect ratio of the compartment	WB	Aux	$\mathrm{L:W} = \frac{\mathrm{L}}{\mathrm{W}}$	1.3
	D	plants/ m^2	Planting density	WB	Aux	-	2.3
Water flux management	Q	m^3/d	Flowrate	TW, WB	Aux	For TW: 5 For WB: $Q = Q_{oTW(t-1)}$	3
	Q_o	m^3/d	Overflow rate	CT, TW, WB	Aux	-	
	Q_r	m^3/d	Recirculation rate	CT, WB	Aux	-	

	Q_d	m^3/d	Discharge rate	EqT2	Aux	-
Plants parameters	K_{et}	-	Crop coefficient of the treatment wetland vegetation	TW	Ext	$\mathrm{K_{et}} = \frac{\mathrm{ET_{tw}}}{\mathrm{ET_0}}$ (ref. 1)
	LAI_{border}, LAI_{center}	m^2/m^2	Leaf area index, *i.e.* area of leaf per area of ground, either at the border or the center of the WB	WB	Ext/ Aux	See figure 5
	W_{border}, W_{center}	-	Number of willows planted either at the border or in the center of the WB		Aux	$W_{border} = D \cdot [L + (W - 2)]$ $W_{center} = D \cdot A - W_{border}$
	LAI	m^2/m^2	Leaf area index adjusted according to aspect ratio	WB	Aux	$\mathrm{LAI} = \frac{\mathrm{LAI_{border}} \cdot \mathrm{WI_{border}} + \mathrm{LAI_{center}} \cdot \mathrm{W_{center}}}{\mathrm{A}}$
	LAI_{act}	m^2/m^2	Proportion of the leaf area index capable of transpiring	WB	Ext	$\mathrm{LAI_{act}} = 1.2 \cdot \mathrm{LAI_{adj}}$ (ref. 1)
	I	%	Percentage of rainfall intercepted by the leaf canopy	WB	Ext	$\mathrm{I} = 3.01 \cdot \mathrm{LAI} + 1.12$ (ref. 2)
	$\bar{G}_s$	mm/d	Average stomatal conductance of the willow bed	WB	Ext	$\bar{\mathrm{G}}_\mathrm{s} = \sum \alpha \cdot \bar{\mathrm{g}}_\mathrm{s}^\mathrm{x}$ (ref. 1)

Evapotranspiration	ET_0	mm/d	Penman-Monteith reference evapotranspiration	-	Ext	$\mathrm{ET_0} = \frac{0{,}408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{900}{T+273} \cdot \upsilon_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0{,}34 \cdot \upsilon_2)}$ (ref. 3)
	E	mm/d	Free water surface evaporation	CT	Ext/ Aux	$\mathrm{E} = 0.8 \cdot \mathrm{ET_0}$ (ref. 1)
	$ET_{tw,}$	mm/d	Evapotranspiration rate of the treatment wetland (TW)	TW	Ext/ Aux	$\mathrm{ET_{tw}} = \mathrm{K_{et}} \cdot \mathrm{ET_0}$ (ref. 1)
	ET_{wb}	mm/d	Evapotranspiration rate of the willow bed (WB)	WB	Ext/ Aux	$\mathrm{ET_{wb}} = \bar{\mathrm{G}}_\mathrm{s} \cdot \mathrm{LAI_{act}} \cdot \frac{\mathrm{VPD}}{\mathrm{p}}$ (ref. 1)
	αF	-	ET coefficient related to fertilization	WB	Aux	1.51
	αS	-	ET coefficient related to substrate type	WB	Aux	0.65
Meteorology	T, T_{min}, T_{max}	°C	Mean, minimal and maximal daily temperature	-	Ext	-
	RH, RH_{min}, RH_{max}	%	Mean, minimal and maximal daily relative humidity	-	Ext	-

υ	m/s	Mean daily wind speed	-	Ext	-
R	W/m^2	Solar radiation	-	Ext	-
P	mm/d	Total daily rainfall	-	Ext	-
p	kPa	Sea level barometric pressure	-	Ext	1.0325
VPD	kPa	Water vapor pressure deficit	-	Ext	$VPD = \frac{e°(T_{max})+e°(T_{min})}{2} - \frac{e°(T_{min})\frac{RH_{max}}{100}+e°(T_{max})\frac{RH_{min}}{100}}{2}$ (ref. 3)

Ref. 1 Frédette *et al.*, 2019, **ref. 2** Stephen, 2005, **ref. 3** Allen *et al.*, 1988

Table 5.2 Results of a 20-year simulation (1995-2015) of the complete operation of a zero liquid discharge water treatment system using an evapotranspiration willow bed. The general system design, flow rate management rules, parameters used list and design code signification are presented in Figure 1, Table 1, Table 2 and Figure 2, respectively. Values in bold for design 1.3OrLf represent the actual design of the reference site. aWB = surface area of the willow bed, ETwb = evapotranspiration of the willow bed, Veqt2 = volume required for the second equalization tank, OF = overflow (volume of water being discharged or pumped out of the system), YWO = years without overflow.

Design code	**aWB (m^2)**	**ET_{wb} (m^3/y)**	**V_{eqt2} (m^3)**	**OF (m^3/y)**	**YWO (y/20y)**	**EqT2 sizing equation**
1.3SaLf	21	15 ± 7	663	1620 ± 839	10	$V_{EqT2} = 1.1[0.00011{A_{WB}}^2 + 0.32A_{WB} + 600 - (Vmax_{WB} - Vmin_{WB})]$
1.3SaHf	5110	4740 ± 633	4940	0	0	$V_{EqT2} = 1.1[0.00010{A_{WB}}^2 + 0.32A_{WB} + 640 - (Vmax_{WB} - Vmin_{WB})]$
1.3OrLf	**5280**	**4910 ± 659**	**2780**	**0**	**0**	$\boldsymbol{V_{EqT2} = 1.1[0.000080{A_{WB}}^2 + 0.28A_{WB} + 690 - (Vmax_{WB} - Vmin_{WB})]}$
1.3OrHf	1450	2000 ± 369	1250	0	0	$V_{EqT2} = 1.1[0.00012{A_{WB}}^2 + 0.22A_{WB} + 720 - (Vmax_{WB} - Vmin_{WB})]$
10SaLf	10	34 ± 7	590	1230 ± 723	13	$V_{EqT2} = 1.1[0.00001{A_{WB}}^2 + 0.6A_{WB} + 510 - (Vmax_{WB} - Vmin_{WB})]$
10SaHf	4840	4480 ± 503	3980	0	0	$V_{EqT2} = 1.1[0.00011{A_{WB}}^2 + 0.19A_{WB} + 720 - (Vmax_{WB} - Vmin_{WB})]$
10OrLf	4000	3910 ± 546	2670	0	0	$V_{EqT2} = 1.1[0.00011{A_{WB}}^2 + 0.36A_{WB} + 600 - (Vmax_{WB} - Vmin_{WB})]$
10OrHf	1270	2080 ± 484	1380	0	0	$V_{EqT2} = 1.1[0.00011{A_{WB}}^2 + 0.31A_{WB} + 790 - (Vmax_{WB} - Vmin_{WB})]$

Chapitre 6 | Synthèse générale

6.1 Retour sur les objectifs

6.1.1 Objectif 1

Le premier objectif de mon projet de recherche était de déterminer la capacité d'évapotranspiration de *Salix miyabeana* (SX67) en marais filtrant. Cet objectif a été atteint, principalement par l'élaboration d'un modèle mathématique permettant de calculer l'évapotranspiration sur la base des paramètres foliaires et de données météorologiques. La méthode du bilan hydrique a aussi été utilisée, mais n'a pas permis à elle seule de déterminer la capacité d'évapotranspiration en raison du mauvais fonctionnement des appareils mesurant les flux d'entrée et de sortie d'eau du marais. Le chapitre 3 de la présente thèse rapporte les résultats de cet objectif.

Quant à l'hypothèse reliée à cet objectif stipulant que *dans le sud du Québec, l'évapotranspiration annuelle de* Salix miyabeana *en marais filtrant par unité de surface dépasse les précipitations annuelles, ce qui rend possible la conception d'un système à effluent nul dans le sud du Québec* **(H1)**, elle a été validée (Tableau 1).

Tableau 6.1 Précipitations totales annuelles pour la région de Montréal comparée à la quantité d'évapotranspiration calculée pour une marais de saules dans la même région (voir chapitre 3), de 2016 à 2018

Année	Précipitations annuelles (mm)	Évapotranspiration cumulative estimée de mai à novembre (mm)	Différence
2016	1040	3790	2750
2017	1260	2490	1230
2018	1050	2180	1130

La réalisation de l'objectif 1 a par ailleurs permis de récolter plusieurs informations et données pertinente pour la réalisation de l'objectif 3, notamment concernant la variation de l'évapotranspiration en fonction de l'âge des tiges et le mode de gestion optimal du flux d'eau dans le système.

6.1.2 Objectif 2

Le second objectif de cette thèse était de mesurer la réponse écophysiologique de *Salix miyabeana* (SX67) à un gradient de concentration de contamination à l'ACC et au PCP. La réalisation de cet objectif est rapportée dans le chapitre 4 de la présente thèse. Il n'a malheureusement pas été possible d'atteindre des concentrations de contaminants suffisamment élevées pour atteindre le seuil de phytotoxicité du saule.

L'hypothèse selon laquelle *Salix miyabeana est une espèce de saules tolérante aux concentrations de contaminants mixtes (ACC et PCP) retrouvées dans le lixiviat brut d'un site de stockage de poteaux traités* **(H2)** est donc vérifiée, du moins sur une période de 16 semaines.

La réalisation de l'objectif 2 a permis d'obtenir plusieurs données intéressantes, notamment concernant l'influence du type de substrat sur l'évapotranspiration. Le seuil de tolérance de *Salix miyabeana* (SX67) à une contamination mixte en ACC et en PCP n'a toutefois pas pu être déterminé.

6.1.3 Objectif 3

Le troisième et dernier objectif de mon projet de recherche était de concevoir et optimiser un système de traitement d'eau à effluent nul par marais de saules. Cet objectif a été réalisé par le biais de la modélisation et fait l'objet du chapitre 5 de la présente thèse. Les résultats de modélisation présentés dans le chapitre 5 sont basés directement sur les caractéristiques du système actuellement en place chez Hydro-Québec, de sorte que les résultats présentés peuvent être appliqués directement à cette étude de cas. Le chapitre 5 présente toutefois aussi une vision plus large de l'utilisation des marais à effluent nul et permet d'extrapoler les résultats à d'autres circonstances.

Quant à l'hypothèse initialement proposée pour cet objectif comme quoi *la modélisation hydrologique d'un système de traitement de lixiviat à effluent nul par marais de saules permet de concevoir un système flexible pouvant gérer, sur un horizon de 20 ans, la variation annuelle et intra-annuelle des précipitations et de l'évapotranspiration* **(H3)**, elle a pu être validée.

La modélisation du système a aussi permis de mettre en évidence que la principale limite de la technologie des marais à effluent nul en climat nordique est l'espace de stockage requis résultant de la forte saisonnalité du climat et de l'évapotranspiration, avec plusieurs centaines, voire milliers, de mètres cubes requis pour l'entreposage de lixiviat, dépendamment de la surface de collecte des lixiviats. De plus, l'intégration au modèle de l’optimisation de l’évapotranspiration a été nécessaire pour démontrer la faisabilité de cette technologie. Sans optimisation de l’évapotranspiration et une gestion appropriée du flux d’eau dans le système, il est impossible d’atteindre l’objectif de l’effluent nul, sur une base annuelle et pour une période prolongée (20 ans).

6.2 Limites des résultats de recherche

6.2.1 Chapitre 2

Les données présentées dans cet article ne sont pas directement applicables à des fins de conception. Il s’agit plutôt d'un outil conceptuel pour appréhender la variation de l'évapotranspiration dans des conditions données. Il peut aussi informer directement le praticien de la réponse d’un cultivar spécifique à différents facteurs et lui fournir des références bibliographiques sur le cultivar. Par ailleurs, certains paramètres fortement associés au potentiel d’évapotranspiration comme le déficit de pression de vapeur dans l’air et la localisation géographique ne sont pas inclus dans cette analyses, tel que discuté dans l’article lui-même, et pour des raisons méthodologiques. Toutefois, il demeure que ces paramètres sont essentiels à considérer et peuvent expliquer un partie de la variation de l’évapotranspiration. Quant aux analyses statistiques choisies, il faut noter qu’elles ne tiennent pas compte de certains biais généralement associés au méta-analyses, notamment que toutes les valeurs factorielles n’était pas systématiquement disponible pour chaque variable réponse (plan incomplet). En fonction de l’objectif général de cette étude, une approche plus exploratoire telle une analyse de correspondance aurait pu s’avérer plus appropriée.

6.2.2 Chapitre 3

Une des limites de cette étude, par ailleurs énoncée dans l'article, est le manque de précisions et de fiabilité des données de bilan hydrique dû au mauvais fonctionnement des appareils de mesure. Un étalonnage plus fréquent des compteurs aurait pu être effectué périodiquement pendant la saison d'exploitation, ce qui n'a pas été fait notamment en raison des normes de sécurité de l'entreprise qui ne me permettaient pas d'effectuer ces étalonnages moi-même, sur le site. Cependant, pour les besoins de cette étude, j'ai conclu que le calibrage des compteurs après la première saison associé à un accord général entre les valeurs d'évapotranspiration modélisées et mesurées (bilan hydrique) pour la deuxième saison, indiquait que les données était suffisamment fiable. Ensuite, aucune analyse de sensibilité n'a été effectuée sur le modèle d'évapotranspiration, mais il est évidement qu'une variation des 2 principaux facteurs du modèle (surface foliaire et conductance stomatique) auront des effets important sur les résultats du modèle. L'effet de telles variations est toutefois observable dans le chapitre 5, ou la variation de la surface foliaire et de la conductance sont les principaux facteurs variant selon le plan de conception. Finalement, certains facteurs affectant l'évapotranspiration tel le type de sol et l'âge des tiges n'ont pas été considérés dans le chapitre 3, mais sont abordés dans les chapitres 4 et 5.

6.2.3 Chapitre 4

Une des principales limites de l'étude présentée au chapitre 4 est le fait de ne pas avoir obtenue des concentrations de contaminant suffisamment élevées pour engendre une réponse phytotoxique des végétaux. Il aurait aussi été intéressant d'étudier plus en détails la spéciation de l'arsenic et du chrome ainsi que la biodisponibilité des différents contaminants, ce qui a été écarté principalement pour des raisons budgétaires. Ensuite, l'infestation de tétranyque subit durant l'expérimentation a légèrement réduite la puissance de nos analyses statistiques et empêcher le prolongement de l'expérimentation jusqu'à la toute fin de la saison de croissance. A postériori, une erreur a été observée dans le modèle statistique utilisé pour évaluer l'effet des facteurs «traitement» et «substrat», soit l'inclusion du facteur bloc comme un facteur régulier plutôt qu'un facteur aléatoire. Les analyses ont été reproduites en corrigeant cette erreur, et de très légères variation des résultats ont été obtenues : 1) détection d'un effet du bloc sur la transpiration et la conductance en fonction du traitement et sur l'évapotranspiration en fonction du substrat (non détecté dans le modèle précédent), 2) différence significative entre l'ET du substrat de coco et du substrat organique, 3) détection d'un effet significatif du type de substrat sur le ratio «root:shoot». Malgré ces modifications, les conclusions de l'études demeurent inchangées.

6.2.4 Chapitre 5

D'une part, le modèle présenté dans ce chapitre peut être considéré comme relativement compliqué et demande une quantité de données initiales non négligeable. Dans une optique de dimensionnement de marais filtrants, une approche basée sur l'utilisation de coefficients de plants et des valeurs d'évapotranspiration de référence sont plus fréquemment utilisées. Toutefois, l'utilisation du modèle basé sur la surface foliaire et la conductance stomatique permet d'inclure des facteur de variation difficilement transférables à la méthode des coefficients de plants. De plus, pour un nouvel emplacement et/ou un nouveau cultivar, les coefficients de plants ne sont pas toujours disponibles. Cette approche reste néanmoins intéressante dans le cas ou de tel coefficient serait disponibles et que les données de surface foliaire et de conductance sera difficilement accessible. Il est toutefois probable qu'un approche par coefficient de plant ne permette pas de concevoir un système aussi flexible (coefficient souvent disponible en valeur annuelle seulement donc ne considérant pas la variation saisonnière du coefficient) et entraîne un surdimensionnement du marais. D'autre part, les coefficients utilisés dans le modèle pour inclure l'effet du substrat et de l'âge des tiges ont été déterminés sur la base unique des travaux présentés dans cette thèse. Il s'agit donc d'une première étape exploratoire et leur utilisation permet d'apprécier leur importance potentielle dans le processus de conception, mais ne constitue pas des valeurs robustes pouvant être utilisées sans nuances. Des revues de littératures ou des expérimentations supplémentaires permettraient de renforcer ces coefficients.

6.3 Limites des marais à effluent nul

6.3.1 Espace et volume requis

L'une des principales contraintes liées au fait d'utiliser un marais plutôt que les technologies conventionnelles est l'espace requis. En effet, tel que démontré lors de la modélisation d'un SEN par marais de saules (Chapitre 5), plusieurs centaines, voire milliers, de mètre carré de marais sont nécessaires, dépendamment de la surface de zone de collecte des lixiviats. Par ailleurs, dans un climat comme celui du Québec où les précipitations et la variation annuelle de l'ET sont élevées, un volume de stockage considérable est requis. Cet aspect souligne l'importance de prendre en compte la variabilité de l'ET et des précipitations dans le temps afin de ne pas surdimensionner le système, ainsi que de maximiser l'ET afin de réduire au maximum la taille de marais requise. Quant à l'espace de stockage, certaines modifications de conception pourraient réduire les besoins. Par exemple, dans notre étude de cas, le dimensionnement de du premier bassin d'équilibre était basé sur la dimension bassin de collecte actuellement présent site de référence (2240 m^2, 543 m^3). Pour une même surface de bassin, une simple augmentation de la profondeur de celui-ci réduirait considérablement le besoin de volume de stockage pour équilibrer ce compartiment, tout en réduisant les risques de débordement au printemps. Ensuite, le plan de conception présenté au chapitre 5 prévoit 2 bassins d'équilibre afin de séparer les lixiviats bruts ou prétraités des lixiviat traités (i.e. étant passé à travers une étape de prétraitement et à travers le marais de saules). L'utilisateur d'un SEN par marais de saules pourrait cependant décider de combiner les 2 bassins en un seul, ce qui optimiserait la gestion des flux hydriques et réduirait à nouveau considérablement le volume de stockage requis. Cette option implique toutefois qu'il pourrait être plus difficile de décharger un volume occasionnel du bassin d'équilibre, car l'eau traitée serait mélangée aux lixiviats bruts. Une simple modification du modèle présenté au chapitre 5 (*i.e.* augmentation de la profondeur du bassin de collecte de 25 cm à 75 cm et utilisation d'un seul bassin d'équilibre) permet de comparer les besoins de stockage et de surface de marais pour le site de l'étude de cas (Tableau 2).

Tableau 6.2 Taille de marais de saules (A_{MS}), potentiel d'évapotranspiration annuel moyen du marais de saules (ET_{MS}), volume total de stockage (V_{EqT}), volume moyen de surverse sur 20 ans (S) et nombre d'années avec surverse sur 20 ans (AVS) pour 3 plan de conception d'un système de traitement de lixiviat à effluent nul par marais de saule. *1.3OrLf* = conception actuelle du système de traitement de l'étude de cas, *10OrHf* = conception optimisée présentée au chapitre 5 de la présente thèse, *1.3OrLf_{modifié}* = conception modifiée du système de traitement de l'étude de cas.

Design code	**A_{MS} (m²)**	**ET_{MS} (m³/a)**	**V_{EqT} (m³)**	**S (m³/a)**	**AVS (a/20a)**
1.3OrLf	5280	4910 ± 659	4690	0	0
10OrHf	1270	2080 ± 484	3290	0	0
$1.3OrLf_{modifié}$	1360	1320 ± 153	1360	24	2

Finalement, on peut supposer que les besoins en volume de stockage et en surface de marais devraient être beaucoup moins importants dans les zones au climat plus sec, aux variations de température moins importantes et au potentiel annuel d'ET plus élevé.

6.3.2 Durée de vie des marais à effluent nul

Comme toute infrastructure de traitement, les marais à effluent nul possèdent une durée de vie déterminée. Toutefois, aucune information précise n'est actuellement rapportée à ce sujet dans la littérature. Dans le cadre de l'étude de cas présentée ici, le cultivar utilisé pour le marais de saules (*S. miyabeana* 'SX67') s'est montré tolérant à une concentration beaucoup plus élevée (lixiviat brut) que celle de l'affluent du marais (lixiviat prétraité; Frédette *et al.*, 2019c). En effet, après plus de 6 ans d'opération, les saules sont toujours vigoureux et ne présentent aucun symptôme important de phytotoxicité. Par ailleurs, l'échantillonnage du substrat du marais de 2016 à 2018 n'a pas permis d'observer une accumulation des contaminants (Figure 1). On pourrait supposer que la durée de vie d'un marais de saules, dans ce cas, dépasse 10 ans.

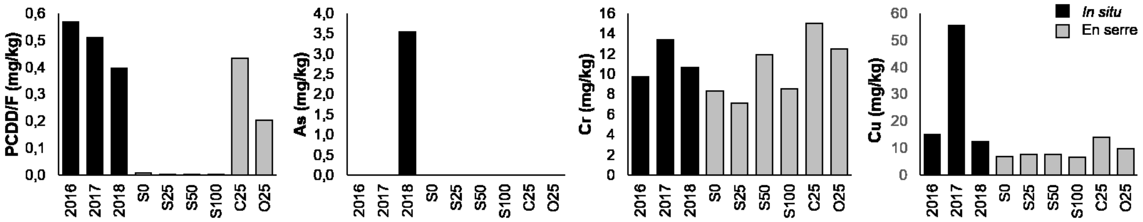

Figure 6.1 Concentration de contaminants mesurée dans le substrat d'un marais de saules irrigué avec un lixiviat prétraité (*in situ*) et dans le substrat de mésocosmes irrigués pendant 12 semaines avec du lixiviat brut ou dilué (en serre).

Dans un système à effluent nul, le marais de saule est dimensionné en fonction de l'évapotranspiration, et non pas en fonction de la charge des contaminants comme c'est le cas pour des marais filtrants traditionnels (Kadlec and Wallace, 2008). Par conséquent, il est attendu que le marais sera surdimensionné en termes de capacité de traitement et on peut donc supposé que sa durée de vie sera supérieure ou au moins égale à celle d'un marais filtrant conventionnel (40-50 ans, Kadlec and Wallace, 2008). Toutefois, il a été rapporté que la durée de vie utile des saules en culture avec rotation de coupe était de 25 à 30 ans (Labrecque et Teodorescu, 2004). Par ailleurs, le traitement préalable des eaux usées, par marais filtrants ou par toute autre technologie, devrait être privilégié afin de garantir une durée de vie maximale. On peut donc supposer que la composante de prétraitement est celle qui accumulera le plus de contaminants et dont la durée de vie sera plus courte.

6.3.3 Destin des contaminants

Comme tout système ou méthode de traitement d'une source de contamination, il est nécessaire de considérer le destin final des contaminants. Dans les cas des systèmes de traitement à effluent nul, une partie des contaminants est typiquement récupérée à une ou plusieurs étapes de traitement, et le résiduel est concentré et disposé comme un solide contaminé selon les normes en vigueur. Dans un SEN par marais de saules, la majorité des contaminants seront concentrés à l'étape de prétraitement. S'il s'agit d'un marais filtrant, on peut supposer que celui-ci aura été conçu pour dégrader la plupart des contaminants organiques et/ou transformer les molécules comme l'ammonium en molécules moins nocives, alors que les métaux et métalloïdes de même que les molécules organiques récalcitrantes seront accumulées principalement dans le substrat du marais, ou encore dans les végétaux. Une fois la durée de vie du marais atteinte, le substrat ainsi que les végétaux devra être disposé selon les méthodes de traitement de sols contaminés disponibles. Il sera aussi important de mesurer la translocation des contaminants dans les parties aériennes des végétaux de même que d'évaluer les risques de transfert trophique, notamment par l'herbivorie. La translocation des contaminants sera aussi à déterminer au niveau du marais de saules, afin que la biomasse récoltée à chaque année puisse être revalorisée sans danger.

6.4 Apport des résultats de recherche

6.4.1 Considération de l'évapotranspiration

L'évapotranspiration est une partie importante du cycle hydrologique de tout système incluant des végétaux. Les résultats de recherche présentés ici démontrent qu'il est particulièrement important de s'intéresser à cette composante du cycle dans le cas d'espèces ligneuses à croissance rapide comme le saule, puisque l'ET peut facilement atteindre et dépasser les précipitations annuelles. Il est connu que l'ET influence la performance des marais filtrants; les résultats de cette étude devraient permettre à des concepteurs. Dans le cas des plantations de saules utilisées pour valoriser des effluents contaminés (*e.g.* eaux usées domestiques, lixiviats), une meilleure connaissance de l'ET permettrait d'améliorer la planification l'irrigation de façon à remplir les besoins hydrologiques de la plantation tout en limitant le drainage potentiel de contaminants. Cette thèse fournit dans un premier temps un document de référence phare pour mieux appréhender l'ET du saule en fonction de ses conditions de croissance (Chapitre 2), mais présente aussi une méthode d'estimation de l'ET facilement reproductible (Chapitre 3). Des travaux sont d'ailleurs en cours afin d'appliquer la méthodologie présentée au Chapitre 3 à une plantation de saules irriguée avec des eaux usées municipales.

6.4.2 Écophysiologie d'un cultivar de saule à croissance rapide

Bien que beaucoup de littérature soit disponible en lien avec la culture de saules à croissance rapide, relativement peu d'études ont trait à la physiologie comme telle de ces espèces et cultivars. Par ailleurs, l'espèce *S. miyabeana*, qui est très souvent utilisée au Québec, demeure peu étudiée comparativement aux cultivars européens, notamment *S. viminalis* et ses nombreux hybrides. La présente thèse propose non seulement une étude complète de l'évapotranspiration de cette espèce, mais aussi plusieurs paramètres physiologiques importants tels la surface foliaire, la phénologie, le taux de croissance, les échanges gazeux, le taux de photosynthèse, la tolérance à une contamination mixte et la réponse à une variation des conditions de croissance. Toutes ces informations pourront être utilisées dans le futur pour les diverses applications de l'espèce en Amérique du Nord, incluant la phytorémédiation, les marais filtrants ou évapotranspirants, les plantations de traitement d'eau usée ou de lixiviat, les plantations de couverture (e.g. couverture de résidus miniers pour limiter le drainage) et la stabilisation de pente ou de bande riveraine.

6.4.3 Alternative pour le traitement d'eau contaminée

En termes de méthodes de traitement des eaux usées, peu d'alternatives aux technologies conventionnelles sont disponibles au Québec. Toutefois, les technologies conventionnelles sont parfois soit obsolètes, inadaptées au contexte, ne permettent pas de répondre à tous les critères de rejet, sont très couteuses, ou encore nécessite une main d'œuvre qualifiée souvent non disponible. Dans certains cas, il est même impossible de mettre en place ces mêmes technologies, fautes de ressources. En contrepartie, l'enjeu du traitement de l'eau demeure au cœur des préoccupations environnementales et les normes de rejets sont appelées à être de plus en plus restrictives. Il apparaît donc essentiel, particulièrement au Québec, d'identifier et de tester des méthodes de traitement alternatives. Les marais filtrants, incluant les marais à effluent nul, sont un bon exemple de ce type de technologie alternative, déjà très répandue ailleurs dans le monde mais pourtant absente au Québec. L'efficacité des marais a pourtant été démontrée à plusieurs reprises, y compris en climat froid similaire au nôtre. Toutefois, moins d'études portent sur les marais à effluent nul. La présente thèse présente les avantages que peuvent représenter les marais à effluent nul pour le traitement d'eau usée, particulièrement de lixiviats, en plus de faire la démonstration théorique de la faisabilité de cette technologie et de proposer des recommandations de conception. Dans le futur, des études à échelle réelle devraient être entreprises afin de valider les concepts théoriques et démontrer de façon concrète l'application des marais de saules à effluent nul, notamment au Québec.

6.5 Opportunités futures

Sur la base des travaux et réflexions présentés dans cette thèse, les axes de recherche futurs sont proposés :

- Détermination précise de seuils de phytotoxicité de différent contaminants pour le saules, en prenant toujours en compte l'effet du substrat;
- Déterminer l'effet de la phytotoxicité de contaminants donnés sur l'évapotranspiration du saule;
- Développer des méthodes d'estimation de la durée de vie de marais à effluent nul en fonction de divers combinaison et concentrations de contaminants;
- Effectuer des revues de littérature ou des expérimentation plus complètes afin de préciser l'influence du substrat et de l'âge des tiges sur l'évapotranspiration du saule;
- Réaliser le dimensionnement et la mise en œuvre d'un marais à effluent nul à échelle pilote ou échelle réelle.

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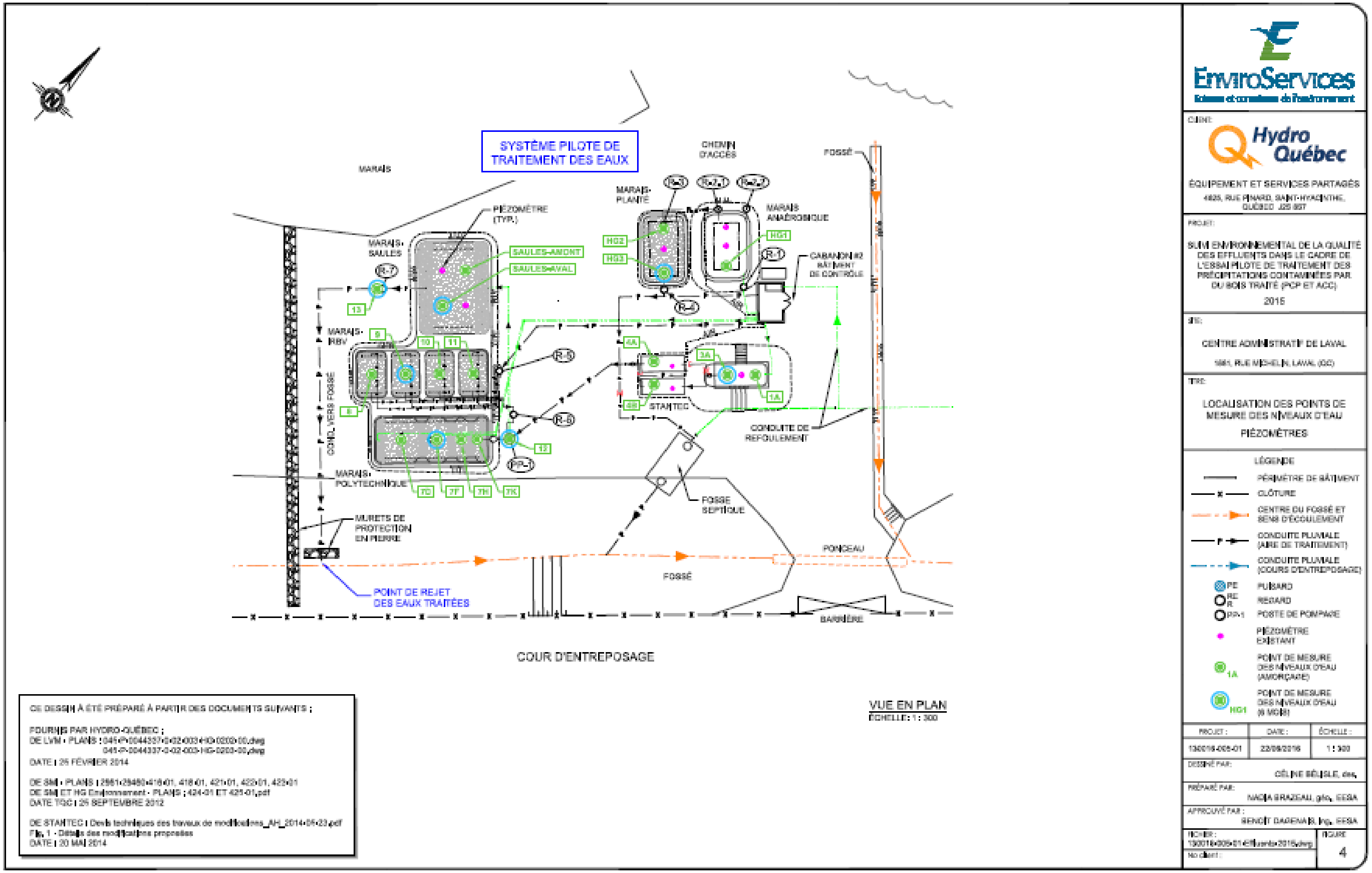
Annexe 1 | Agencement des marais filtrants et des points d'échantillonnage du projet pilote de la cour d'entreposage de poteaux d'Hydro-Québec



CE DESSIN A ÉTÉ PRÉPARÉ À PARTIR DES DOCUMENTS SUIVANTS ;

FOURNIS PAR HYDRO-QUÉBEC ;
DE LVM - PLANS : 045-P-0044337-0-02-003-HG-0202-00.dwg
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DATE : 26 FÉVRIER 2014

DE SMI - PLANS : 2961-29480-416-01, 418-01, 421-01, 422-01, 423-01
DE SMI ET HG Environnement - PLANS ; 424-01 ET 425-01.pdf
DATE TQC : 25 SEPTEMBRE 2012

DE STANTEC : Devis techniques des travaux de modifications_AH_2014-05-23.pdf
Fig. 1 - Détails des modifications proposées
DATE : 20 MAI 2014

EnviroServices
Sciences et connaissances de l'environnement

CLIENT :
Hydro Québec
ÉQUIPEMENT ET SERVICES PARTAGÉS
4825, RUE PINARD, SAINT-HYACINTHE, QUÉBEC J2S 8S7

PROJET :
SUIVI ENVIRONNEMENTAL DE LA QUALITÉ DES EFFLUENTS DANS LE CADRE DE L'ESSAI PILOTE DE TRAITEMENT DES PRÉCIPITATIONS CONTAMINÉES PAR DU BOIS TRAITÉ (PCP ET ACC)
2015

SITE :
CENTRE ADMINISTRATIF DE LAVAL
1881, RUE MICHELIN, LAVAL (QC)

TITRE :
LOCALISATION DES POINTS DE MESURE DES NIVEAUX D'EAU
PIÉZOMÈTRES

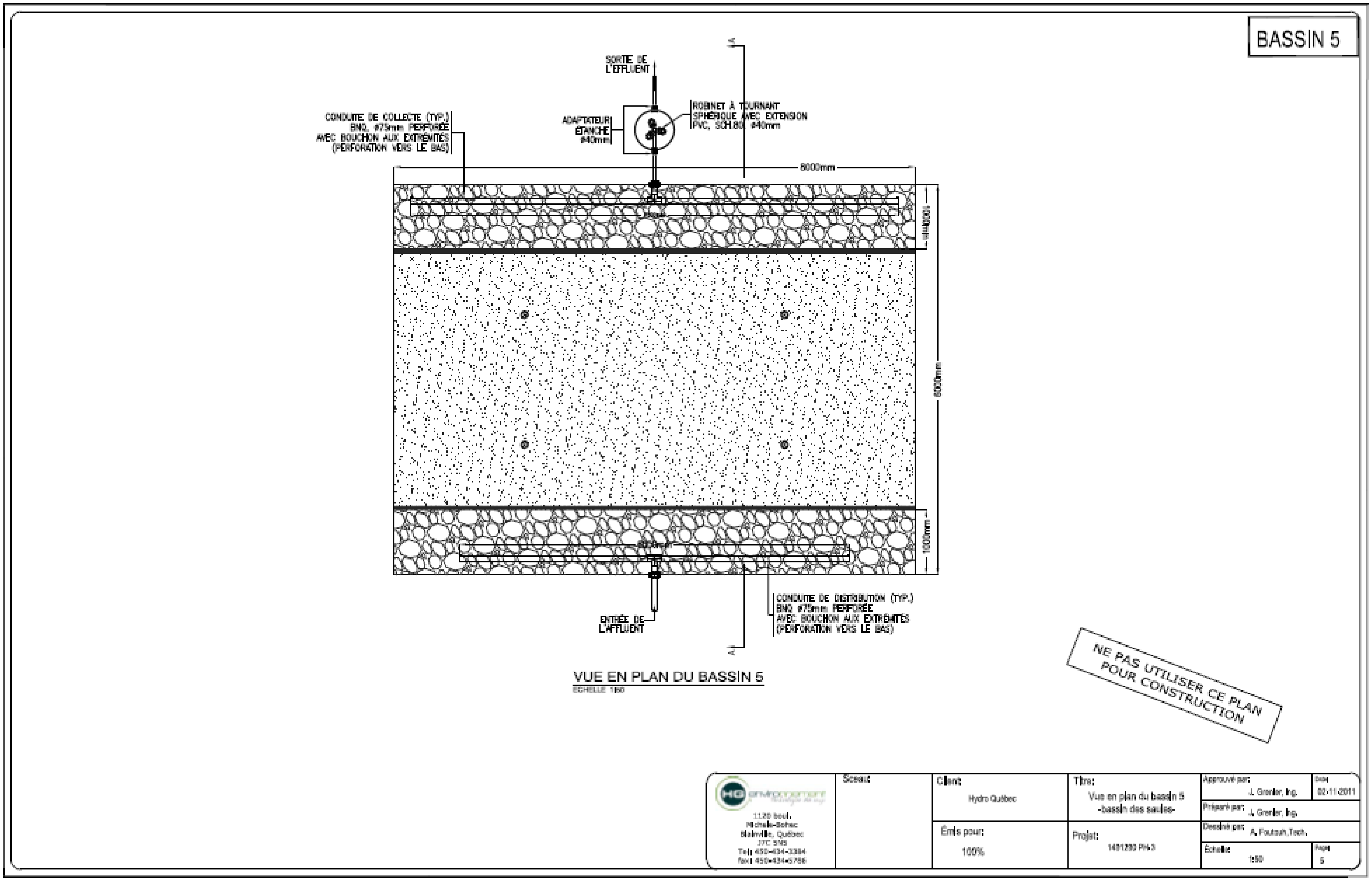
LÉGENDE

━━━	PÉRIMÈTRE DE BÂTIMENT
—x—	CLÔTURE
- - ▶	CENTRE DU FOSSÉ ET SENS D'ÉCOULEMENT
—F→	CONDUITE PLUVIALE (AIRE DE TRAITEMENT)
- - ▶	CONDUITE PLUVIALE (COURS D'ENTREPOSAGE)
◍ PE	PUISARD
○ RE R	REGARD
○ PP-1	POSTE DE POMPAGE
●	PIÉZOMÈTRE EXISTANT
◉ 1A	POINT DE MESURE DES NIVEAUX D'EAU (AMORÇAGE)
◉ HG1	POINT DE MESURE DES NIVEAUX D'EAU (6 MOIS)

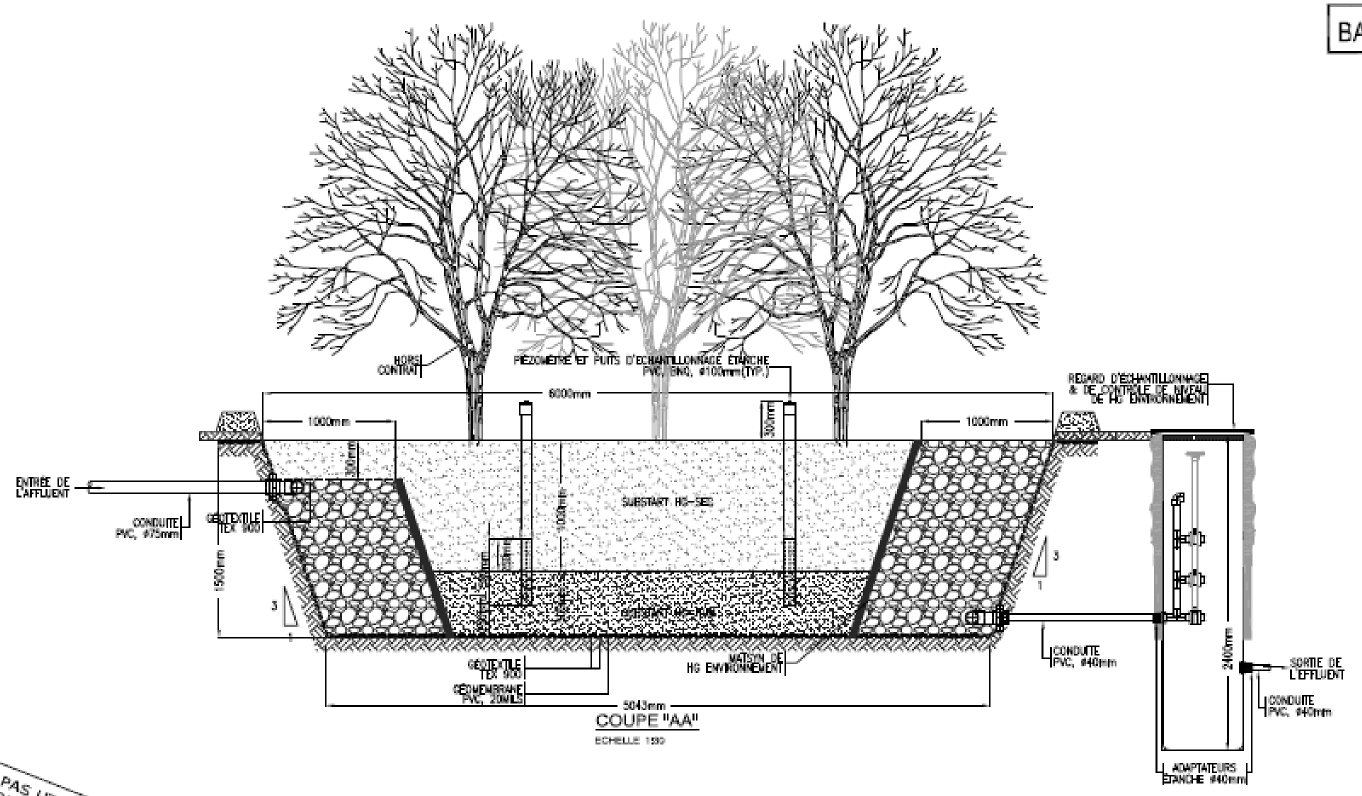
PROJET :	DATE :	ÉCHELLE :
130016-005-01	22/09/2016	1 : 300

DESSINÉ PAR : CÉLINE BÉLISLE, des.
PRÉPARÉ PAR : NADIA BRAZEAU, géo., EESA
APPROUVÉ PAR : BENOÎT DAGENAIS, ing., EESA
FICHIER : 130016-005-01-Effluents-2015.dwg
No client :
FIGURE 4

Annexe 2 | Plans détaillés de la conception du marais filtrants de saules



BASSIN 5



COUPE "AA"

ECHELLE 1:50

NE PAS UTILISER CE PLAN POUR CONSTRUCTION

HG environnement

1120 boul.
Michèle-Bohec
Blainville, Québec
J7C 5N5
Tel: 450-434-3384
fax: 450-434-5788

Sceau:

Client: Hydro Québec

Émis pour: 100%

Titre: Vue en coupe du bassin 5 -bassin des saules-

Projet: 1401280 PH-3

Approuvé par: J. Grenier, Ing.

Date: 02-11-2011

Préparé par: J. Grenier, Ing.

Dessiné par: A. Foutsuh,Tech.

Échelle: Indiquée

Page: 6

Annexe 3 | Base de données brutes créée et utilisée pour la rédaction du Chapitre 2

1er auteur	**Année**	**Espèce**	**Variété**	**Résultat**	**T ou ET**	**Période**	**Note.période**	**Méthode**	**Densité**	**Contexte**	**tiges**	**racines**	**Sol**	**Notes.sol**	**Irrigation**	**Notes.Irri.**	**mm/d**	**Fertilisation**	**Notes.fert.**	**Contamitation**	**Notes.cont.**	**Pays**
Benettin	2019	S.viminalis		10,00	ET	saison	février-june	water balance	1,79	lysimeter	2	2	sa		high		14,67	no		no		suisse
Bialowiec	2003	S.amygdalina	NA	0,55	ET	Saison	99 days	water balance	48,83	Lysimeter	1	1	Gravel	2-3 mm, washed	High	Saturated	NA	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2003	S.amygdalina	NA	1,56	ET	Saison	99 days	water balance	48,83	Lysimeter	1	1	Gravel	2-3 mm, washed	High	Saturated	NA	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2003	S.amygdalina	NA	2,30	ET	Saison	99 days	water balance	48,83	Lysimeter	1	1	Gravel	2-3 mm, washed	High	Saturated	NA	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2003	S.amygdalina	NA	2,03	ET	Saison	99 days	water balance	48,83	Lysimeter	1	1	Gravel	2-3 mm, washed	High	Saturated	NA	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	0,95	ET	Saison	US	water balance	7,00	Lysimeter	1	2	Sand		Low	5 mm/d	2,28	yes	Sewage sludge	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	1,63	ET	Saison	US	water balance	7,00	Lysimeter	1	2	Sand		Low	3 mm/d	2,58	yes	Sewage sludge	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	1,77	ET	Saison	US (184 EST.)	water balance	7,00	Lysimeter	1	1	Sand		Low	1 mm/d	2,61	yes	Sewage sludge	Yes	landfill leachate	Poland

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Bialowiec	2007	S.amygdalina	NA	0,95	ET	Saison	US	water balance	7,00	Lysimeter	1	2	Sand		Low	5 mm/d	2,61	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	2,04	ET	Saison	US	water balance	7,00	Lysimeter	1	1	Sand		Low	1 mm/d	2,99	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	2,17	ET	Saison	US	water balance	7,00	Lysimeter	1	2	Sand		Low	1 mm/d	4,18	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	2,04	ET	Saison	US	water balance	7,00	Lysimeter	1	1	Sand		Low	3 mm/d	4,21	yes	Sewage sludge	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	2,31	ET	Saison	US	water balance	7,00	Lysimeter	1	1	Sand		Low	3 mm/d	4,24	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	2,99	ET	Saison	US	water balance	7,00	Lysimeter	1	2	Sand		Low	1 mm/d	4,24	yes	Sewage sludge	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	1,22	ET	Saison	US	water balance	7,00	Lysimeter	1	2	Sand		Low	3 mm/d	4,35	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	1,09	ET	Saison	US	water balance	7,00	Lysimeter	1	1	Sand		Medium	5 mm/d	5,22	yes	landfill leachate	Yes	landfill leachate	Poland
Bialowiec	2007	S.amygdalina	NA	2,31	ET	Saison	US	water balance	7,00	Lysimeter	1	1	Sand		Medium	5 mm/d	5,30	yes	Sewage sludge	Yes	landfill leachate	Poland

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Borek	2010	S.viminalis	1023, 1047, 1052, 1054	1,38	ET	Annuelle		Modelisation	UK	Plantation	1	UK	Clay	Sandy clay loam	Low	rain only	1,36	no	NA	no	NA	Poland
Borek	2010	S.viminalis	1023, 1047, 1052, 1054	1,71	ET	Annuelle		Modelisation	UK	Plantation	1	UK	Sand	sandy loam	Low	rain only	1,66	no	NA	no	NA	Poland
Budny	2016	S.sp	NA	3,06	T	Saison	June-sept	Modelisation	UK	Floodplain	UK	UK	Peat	NA	High	wetland	NA	no	NA	no	NA	United-States
Conger	2001	S.nigra	NA	10,00	T	Saison	Growing season	Sapflow	2,28	Plantation	3	3	Clay	Silty clay	Medium	sprinkler	NA	no	NA	yes	10 mg/L bentazon	United-States
Conger	2001	S.nigra	NA	13,00	T	Saison	Growing season	Sapflow	2,28	Plantation	4	4	Clay	Silty clay	Low	rain only	NA	no	NA	yes	10 mg/L bentazon	United-States
Conger	2001	S.nigra	NA	6,00	T	Saison	Growing season	Sapflow	3,00	Plantation	3	3	Clay	Silty clay	Medium	sprinkler	NA	no	NA	yes	10 mg/L bentazon	United-States
Conger	2001	S.nigra	NA	12,00	T	Saison	Growing season	Sapflow	3,00	Plantation	4	4	Clay	Silty clay	Low	rain only	NA	no	NA	Yes	10 mg/L bentazon	United-States
Cureton	1991	S.Babylonica		9,26	ET	Ponctuelle	67 jours	water balance	5,10	Lysimeter	1	1	Clay	silty clay	High	NA	NA	no	NA	no	NA	Canada
Cureton	1991	S.Babylonica		9,55	ET	Ponctuelle	67 jours	water balance	5,10	Lysimeter	1	1	Clay	silty clay	High	NA	NA	yes	landfill leachate	yes	landfill leachate	Canada

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Curneen	2014	S.viminalis	Inger	4,74	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Inger	4,75	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Inger	3,38	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Sven	4,36	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Sven	3,93	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Sven	3,11	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	7,61	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	6,95	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	3,56	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Sven	7,38	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	2	Topsoil	Over sand layer	High	192	NA	yes	Primary treated	no	NA	Ireland

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Curneen	2014	S.viminalis	Sven	4,69	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Sven	4,07	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Sven	3,78	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	4,80	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	4,35	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	2,91	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	5,23	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	1,87	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	2,96	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Sven	6,50	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Secondary treated	no	NA	Ireland

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Curneen	2014	S.viminalis	Sven	5,67	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Inger	6,73	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Inger	6,29	ET	Saison	Growing season	water balance	4,35	Lysimeter	1	3	Topsoil	Over sand layer	High	173	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	3,99	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	3,82	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Tordis	3,01	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	4,39	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	3,26	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	3,26	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Inger	3,86	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	yes	Primary treated	no	NA	Ireland

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Curneen	2014	S.viminalis	Inger	3,38	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Inger	2,37	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Inger	3,78	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	no	Rain	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	7,10	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	yes	Primary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	2,68	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2014	S.viminalis	Torhild	4,29	ET	Saison	Growing season	water balance	4,35	Lysimeter	2	4	Topsoil	Over sand layer	High	144	NA	no	Rain	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,93	ET	Saison	4 months	water balance	3,00	Constructed wetland	1	1	Soil	US	High	356,7 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,60	ET	Annuelle	7 months	water balance	3,00	Constructed wetland	1	1	Soil	US	Low	rain only	NA	no	NA	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,48	ET	Annuelle	10 months	water balance	3,00	Constructed wetland	1	2	Soil	US	High	628,4 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,68	ET	Annuelle	10 months	water balance	3,00	Constructed wetland	1	2	Soil	US	High	306,6 L/d	NA	yes	Secondary treated	no	NA	Ireland

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Curneen	2016	S.viminalis	Mixed	2,10	ET	Annuelle	10 months	water balance	3,00	Constructed wetland	1	2	Soil	US	High	306,6 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,50	ET	Annuelle	9 months	water balance	3,00	Constructed wetland	1	2	Soil	US	High	326,8 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,96	ET	Annuelle	NA	water balance	3,00	Constructed wetland	1	2	Soil	US	High	356,7 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,57	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	2	Soil	US	Low	rain only	NA	no	NA	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,55	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	3	Soil	US	High	628,4 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,84	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	3	Soil	US	High	356,7 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,63	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	3	Soil	US	High	306,6 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,27	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	3	Soil	US	High	306,6 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,58	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	3	Soil	US	High	326,8 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,68	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	3	Soil	US	Low	rain only	NA	no	NA	no	NA	Ireland

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Curneen	2016	S.viminalis	Mixed	1,99	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	4	Soil	US	High	628,4 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,06	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	4	Soil	US	High	356,7 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,58	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	4	Soil	US	High	306,6 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,24	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	4	Soil	US	High	306,6 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,15	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	4	Soil	US	High	326,8 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,76	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	4	Soil	US	Low	rain only	NA	no	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,54	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	5	Soil	US	High	628,4 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,32	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	5	Soil	US	High	356,7 L/d	NA	yes	Primary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	1,91	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	5	Soil	US	High	306,6 L/d	NA	yes	Secondary treated	no	NA	Ireland
Curneen	2016	S.viminalis	Mixed	2,55	ET	Annuelle	NA	water balance	3,00	Constructed wetland	2	5	Soil	US	High	306,6 L/d	NA	yes	Secondary treated	no	NA	Ireland

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Dimitriou	2004	S.viminalis	78-183	8,26	ET	Saison	134 days	water balance	2,00	Lysimeter	1	4	Clay	Kungsängen	High	1230 mm	11,04	yes	Wastewater	no	NA	Sweden
Dimitriou	2004	S.viminalis	78-183	7,76	ET	Saison	134 days	water balance	2,00	Lysimeter	1	4	Clay	Kungsängen	High	1230 mm	11,04	yes	Liquid fertilizer	no	NA	Sweden
Dimitriou	2004	S.viminalis	78-183	6,31	ET	Saison	134 days	water balance	2,00	Lysimeter	1	4	Sand	Nantuna	High	1230 mm	11,04	yes	Wastewater	no	NA	Sweden
Dimitriou	2004	S.viminalis	78-183	6,28	ET	Saison	134 days	water balance	2,00	Lysimeter	1	4	Sand	Nantuna	High	1230 mm	11,04	yes	Liquid fertilizer	no	NA	Sweden
Dimitriou	2010	S.viminalis	Tora	4,42	ET	Saison	113 days	water balance	2,00	Lysimeter	2	2	Clay	Kungsängen	Medium	604	5,35	yes	landfill leachate	yes	landfill leachate	Sweden
Dimitriou	2010	S.viminalis	Tora	2,43	ET	Saison	72 days	water balance	2,00	Lysimeter	1	1	Clay	Kungsängen	Medium	431	5,99	yes	landfill leachate	yes	landfill leachate	Sweden
Dimitriou	2010	S.viminalis	Tora	2,15	ET	Saison	72 days	water balance	2,00	Lysimeter	1	1	Clay	Kungsängen	Medium	467	6,49	yes	landfill leachate	yes	landfill leachate	Sweden
Dimitriou	2010	S.viminalis	Tora	7,52	ET	Saison	113 days	water balance	2,00	Lysimeter	2	2	Clay	Kungsängen	Medium	830	7,35	yes	landfill leachate	yes	landfill leachate	Sweden
Dimitriou	2010	S.viminalis	Tora	2,22	ET	Saison	72 days	water balance	2,00	Lysimeter	1	1	Clay	Kungsängen	Medium	539	7,49	yes	landfill leachate	yes	landfill leachate	Sweden
Dimitriou	2010	S.viminalis	Tora	4,87	ET	Saison	113 days	water balance	2,00	Lysimeter	2	2	Clay	Kungsängen	High	1282	11,35	yes	landfill leachate	yes	landfill leachate	Sweden

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Dimitriou	2010	S.viminalis	Tora	2,63	ET	Saison	152	water balance	2,00	Lysimeter	2	4	Clay	Kungsängen	Low	rain only	3,97	yes	Sewage sludge	no	NA	Sweden
Dimitriou	2010	S.viminalis	Tora	2,63	ET	Saison	152	water balance	2,00	Lysimeter	2	4	Sand	Nantuna	Low	rain only	3,97	yes	Sewage sludge	no	NA	Sweden
Dimitriou	2010	S.viminalis	Tora	2,31	ET	Saison	108	water balance	2,00	Lysimeter	1	3	Clay	Kungsängen	Low	rain only	3,99	yes	Sewage sludge	no	NA	Sweden
Dimitriou	2010	S.viminalis	Tora	2,31	ET	Saison	108	water balance	2,00	Lysimeter	1	3	Sand	Nantuna	Low	rain only	3,99	yes	Sewage sludge	no	NA	Sweden
Dimitriou	2010	S.viminalis	Tora	7,89	ET	Saison	152	water balance	2,00	Lysimeter	2	4	Clay	Kungsängen	High	1064 mm	10,97	yes	Wastewater	no	NA	Sweden
Dimitriou	2010	S.viminalis	Tora	5,26	ET	Saison	152	water balance	2,00	Lysimeter	2	4	Sand	Nantuna	High	1064 mm	10,97	yes	Wastewater	no	NA	Sweden
Dimitriou	2010	S.viminalis	Tora	8,33	ET	Saison	108	water balance	2,00	Lysimeter	1	3	Clay	Kungsängen	High	756	10,99	yes	Wastewater	no	NA	Sweden
Dimitriou	2010	S.viminalis	Tora	7,41	ET	Saison	108	water balance	2,00	Lysimeter	1	3	Sand	Nantuna	High	756	10,99	yes	Wastewater	no	NA	Sweden
Doody	2011	S.Babylonica	NA	6,60	ET	Annuelle	NA	Sapflow	UK	Floodplain	UK	UK	UK	NA	High	permanent water	NA	no	NA	no	NA	Australia

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Doody	2011	S.Babylonica	NA	4,81	ET	Annuelle	NA	Sapflow	UK	Floodplain	UK	UK	UK	NA	High	permanent water	NA	no	NA	no	NA	Australia
Doody	2011	S.Babylonica	NA	5,33	ET	Annuelle	NA	Sapflow	UK	Floodplain	UK	UK	UK	NA	High	permanent water	NA	no	NA	no	NA	Australia
Doody	2011	S.Babylonica	NA	1,54	ET	Annuelle	NA	Sapflow	UK	Floodplain	UK	UK	UK	NA	Medium	semi-permanent	NA	no	NA	no	NA	Australia
Doody	2014	S.fragilis		3,50	ET	annual		Sapflow	na	Floodplain	na	na	na		High			no		no		Australia
Duan	2017	S.gordejevii		1,88	T	saison	1 mai- 30 sept	stem flow	3,59	plantation	uk	uk	sand		low	na	na	no	na	no	na	china
Frédette	2018	S.miyabeana	SX67	22,70	ET	Saison		water balance	2,33	Constructed wetland	2-3	5-6	organic	peat and sand	High	saturated	NA	yes		yes		Canada
Frédette	2019	S.miyabeana	SX68	16,50	ET	Saison		Modelisation	2,33	Constructed wetland	2-3	5-6	organic	peat and sand	High	saturated	NA	yes		yes		Canada
Glenn	1998	S.Gooddingii	NA	8,90	T	Périodique	August-september	water balance	20,37	Lysimeter	1	1	Sand	NA	Medium	Constantly moist soil	NA	yes	Liquid fertilizer	no	NA	United-States
Glenn	1998	S.Gooddingii	NA	4,70	T	Périodique	August-september	water balance	20,37	Lysimeter	1	1	Sand	NA	Medium	Constantly moist soil	NA	yes	Liquid fertilizer	yes	2 g/L NaCl	United-States

1er auteur	Glenn	Glenn	Gregersen	Gregersen	Gregersen	Gregersen	Gregersen	Gregersen	Gregersen
Année	1998	1998	2001	2001	2001	2001	2001	2001	2001
Espèce	S.Gooddingii	S.Gooddingii	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis
Variété	NA	NA	Bjorn, Tora, Jorr	Bjorn, Tora, Jorr	Bjorn, Tora, Jorr	Bjorn, Tora, Jorr	Bjorn, Tora, Jorr	Bjorn, Tora, Jorr	Bjorn, Tora, Jorr
Résultat	4,30	2,50	2,68	3,48	3,12	3,10	4,55	2,79	4,03
T ou ET	T	T	ET	ET	ET	ET	ET	ET	ET
Période	Périodique	Périodique	Annuelle	Annuelle	Annuelle	Annuelle	Annuelle	Annuelle	Annuelle
Note.période	August-september	August-september	NA	NA	NA	NA	NA	NA	NA
Méthode	water balance	water balance	water balance	water balance	water balance	water balance	water balance	water balance	water balance
Densité	20,37	20,37	low	low	low	low	low	low	low
Contexte	Lysimeter	Lysimeter	Constructed wetland	Constructed wetland	Constructed wetland	Constructed wetland	Constructed wetland	Constructed wetland	Constructed wetland
tiges	1	1	1	1	1	1	1	1	2
racines	1	1	1	1	1	1	1	1	2
Sol	Sand	Sand	Topsoil	Topsoil	Topsoil	Topsoil	Topsoil	Topsoil	Topsoil
Notes.sol	NA	NA	NA	NA	NA	NA	NA	NA	NA
Irrigation	Medium	Medium	High	High	High	High	High	High	High
Notes.Irri.	Constantly moist soil	Constantly moist soil	rain + wastewater	rain + wastewater	rain + wastewater	rain + wastewater	rain + wastewater	rain + wastewater	rain + wastewater
mm/d	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fertilisation	yes	yes	yes	yes	yes	yes	yes	yes	yes
Notes.fert.	Liquid fertilizer	Liquid fertilizer	Primary treated	Primary treated	Primary treated	Primary treated	Primary treated	Primary treated	Primary treated
Contamitation	yes	yes	no	no	no	no	no	no	no
Notes.cont.	4 g/L NaCl	8 g/L NaCl	NA	NA	NA	NA	NA	NA	NA
Pays	United-States	United-States	Denmark	Denmark	Denmark	Denmark	Denmark	Denmark	Denmark

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Gregersen	2001	S.viminalis	Bjorn, Tora, Jorr	5,73	ET	Annuelle	NA	water balance	low	Constructed wetland	2	2	Topsoil	NA	High	rain + wastewater	NA	yes	Primary treated	no	NA	Denmark
Gregersen	2001	S.viminalis	Bjorn, Tora, Jorr	4,52	ET	Annuelle	NA	water balance	low	Constructed wetland	2	2	Topsoil	NA	High	rain + wastewater	NA	yes	Primary treated	no	NA	Denmark
Gregersen	2001	S.viminalis	Bjorn, Tora, Jorr	4,63	ET	Annuelle	NA	water balance	low	Constructed wetland	2	2	Topsoil	NA	High	rain + wastewater	NA	yes	Primary treated	no	NA	Denmark
Gregersen	2001	S.viminalis	Bjorn, Tora, Jorr	2,68	ET	Annuelle	NA	water balance	low	Constructed wetland	2	2	Topsoil	NA	High	rain + wastewater	NA	yes	Primary treated	no	NA	Denmark
Gregersen	2001	S.viminalis	Bjorn, Tora, Jorr	5,15	ET	Annuelle	NA	water balance	low	Constructed wetland	2	2	Topsoil	NA	High	rain + wastewater	NA	yes	Primary treated	no	NA	Denmark
Grip	1989	S.viminalis	77683, 77666	3,01	ET	Saison	28 april-19 october	Modelisation	UK	Lysimeter	1	3	Sand	sandy loam	Low	rain + low irrigation	NA	no	NA	no	NA	Sweden
Guidi	2008	S.alba	SI62-059	3,44	ET	Saison	20 april-20 october	water balance	1,88	Lysimeter	1	1	sand	loamy soil	Medium	field capacity	NA	no	NA	no	NA	Italy
Guidi	2008	S.alba	SI62-059	6,61	ET	Saison	20 april-20 october	water balance	1,88	Lysimeter	1	1	sand	loamy soil	Medium	field capacity	NA	yes	263 kg/ha	no	NA	Italy
Guidi	2008	S.alba	SI62-059	5,93	ET	Saison	20 may-10 october	water balance	1,88	Lysimeter	2	2	sand	loamy soil	Medium	field capacity	NA	no	NA	no	NA	Italy
Guidi	2008	S.alba	SI62-059	11,93	ET	Saison	20 may-10 october	water balance	1,88	Lysimeter	2	2	sand	loamy soil	Medium	field capacity	NA	yes	383 kg/ha	no	NA	Italy

Hartwich	Hartwich	Hartwich	Halldin	Hall	Guidi	Guidi	Guidi	Guidi	**1er auteur**
2016	2016	2016	1989	1998	2014	2014	2010	2010	**Année**
S.sp	S.sp	S.sp	S.sp	S.bujartica	S.miyabeana	S.miyabeana	S.viminalis	S.viminalis	**Espèce**
NA	NA	NA	NA	Germany	SX67	SX67	SQV 5027	SQV 5027	**Variété**
1,32	1,11	1,35	3,14	4,75	6,19	5,53	6,28	6,02	**Résultat**
ET	ET	ET	ET	T	ET	ET	ET	ET	**T ou ET**
Annuelle	Annuelle	Annuelle	Saison	Saison	Saison	Saison	Saison	Saison	**Période**
NA	NA	NA	6 mois	15 mai au 6 sept (114)	140 days	140 days	90 days	90 days	**Note.période**
Modelisation	Modelisation	Modelisation	Modelisation	Sapflow	Modelisation	Modelisation	water balance	water balance	**Méthode**
UK	UK	UK	UK	UK	1,95	1,95	14,14	14,14	**Densité**
Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	Lysimeter	Lysimeter	**Contexte**
UK	UK	UK	UK	3	2	1	1	1	**tiges**
UK	UK	UK	UK	4	2	1	1	1	**racines**
UK	UK	UK	Clay	Clay	Topsoil	Topsoil	Topsoil	Topsoil	**Sol**
NA	NA	NA	NA	clay loam	on 30 cm	on 30 cm	potting mix	potting mix	**Notes.sol**
Low	Low	Low	Low	Low	Medium	Medium	medium	High	**Irrigation**
Rain only	Rain only	Rain only	Rain only	Rain only	rain + deficit irrigation	rain + deficit irrigation	field capacity	field capacity x 5	**Notes.Irri.**
2,23	1,57	1,55	NA	1,88	6,19	5,53	NA	NA	**mm/d**
no	no	no	no	no	no	no	yes	yes	**Fertilisation**
NA	NA	NA	NA	NA	NA	NA	220 kg/ha	220 kg/ha	**Notes.fert.**
no	no	no	no	no	no	no	no	no	**Contamitation**
NA	NA	NA	NA	NA	NA	NA	NA	NA	**Notes.cont.**
Germany	Germany	Germany	Sweden	United-Kingdom	Canada	Canada	Canada	Canada	**Pays**

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Hartwich	2016	S.sp	NA	1,38	ET	Annuelle	NA	Modelisation	UK	Plantation	UK	UK	UK	NA	Low	Rain only	2,47	no	NA	no	NA	Germany
Huang	2014	S.psammophila	NA	1,48	T	Ponctuelle	29may - 13 july	Sapflow	UK	Plantation	UK	UK	Sand	Aeolian sand	Low	rain only	1,56	no	NA	no	NA	China
Huang	2015	S.psammophila		1,44	ET	Saison	26 april - 27 sept	Modelisation	0,02	Plantation	UK	UK	sand	na	Low	na	NA	no	NA	no	NA	china
Iritz	2001	S.viminalis	NA	2,61	ET	Saison	184 days	Modelisation	2,00	Plantation	1	3	Clay	NA	Low	Rain + drip irrigation	3,10	yes	50 kg/ha	no	NA	Sweden
Irmak	2013	S.amygdaloides	NA	3,50	T	Saison	129 days	Modelisation	UK	Floodplain	UK	UK	Sand	loamy sand	High	flooding	NA	no	NA	no	NA	United-States
Jing	2010	S.Babylonica	NA	2,45	ET	Ponctuelle	13sept-21nov	water balance	UK	Constructed wetland	1	1	Gravel		High	saturated	NA	yes	Wastewater	no	NA	China
Kabenge	2012	S.amygdaloides	NA	5,22	ET	Saison	186 days	Modelisation	UK	Floodplain	UK	UK	Sand	loamy sand	High	flooding	NA	no	NA	no	NA	United-States
Kabenge	2012	S.amygdaloides	NA	3,62	ET	Saison	186 days	Modelisation	UK	Floodplain	UK	UK	Sand	loamy sand	Medium	river bed	NA	no	NA	no	NA	United-States

1er auteur	**Année**	**Espèce**	**Variété**	**Résultat**	**T ou ET**	**Période**	**Note.période**	**Méthode**	**Densité**	**Contexte**	**tiges**	**racines**	**Sol**	**Notes.sol**	**Irrigation**	**Notes.Irri.**	**mm/d**	**Fertilisation**	**Notes.fert.**	**Contamitation**	**Notes.cont.**	**Pays**
Kucerova	2001	S.cinerea	NA	21,60	ET	Ponctuelle	June-July	water balance	UK	Constructed wetland	UK	UK	Sand	sandy substrate	High	constantly	NA	yes	Wastewater	no	NA	Belgium
Linderson	2007	S.dasyclados	Loden	1,31	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Rain onay	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.dasyclados	Loden	1,63	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Dry	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	L78183	1,33	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Rain only	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	L78183	1,14	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Dry	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	Jorr	2,12	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Rain only	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	Jorr	1,57	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Dry	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	Jorunn	0,98	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Rain only	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	Jorunn	0,65	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Dry	2,58	no	NA	no	NA	Sweden

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Linderson	2007	S.viminalis	Rapp	1,63	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Rain only	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	Rapp	1,90	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Dry	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	Tora	1,80	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Rain only	2,58	no	NA	no	NA	Sweden
Linderson	2007	S.viminalis	Tora	0,98	T	Saison	may-september	Sapflow	2,40	Plantation	UK	3	Clay	NA	Low	Dry	2,58	no	NA	no	NA	Sweden
Lindroth	1994	S.viminalis	NA	2,99	ET	Saison	may-october	Modelisation	2,00	Plantation	3	3	Clay	NA	Low	Rain + drip irrigation	3,40	yes	300 kg/ha	no	NA	Sweden
Lindroth	1994	S.viminalis	NA	2,89	ET	Saison	may-october	Modelisation	2,00	Plantation	2	5	Clay	NA	Low	Rain + drip irrigation	3,53	yes	50 kg/ha	no	NA	Sweden
Marmiroli	2012	S.kinuyanagi	NA	5,43	ET	Saison	october-february	water balance	2,20	Lysimeter	1	1	Sand	loamy sand	High	NA	NA	yes	dairy effluent	yes	dairy effluent (cl)	New-Zeland
Marmiroli	2012	S.kinuyanagi	NA	5,26	ET	Saison	october-february	water balance	2,20	Lysimeter	1	1	Sand	loamy sand	High	NA	NA	yes	dairy effluent	yes	dairy effluent (cl)	New-Zeland
Marmiroli	2012	S.kinuyanagi	NA	4,92	ET	Saison	october-february	water balance	2,20	Lysimeter	1	1	Sand	loamy sand	High	NA	NA	yes	dairy effluent	yes	dairy effluent (cl)	New-Zeland

Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Martin	Marmiroli	**1er auteur**
2006	2006	2006	2006	2006	2006	2006	2006	2006	2012	**Année**
S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.kinuyanagi	**Espèce**
Jorr	Jorr	Jorr	Jorr	Jorr	Jorr	Jorr	Jorr	Jorr	NA	**Variété**
8,05	26,71	14,34	12,33	8,52	8,07	4,03	3,36	2,24	4,58	**Résultat**
ET	ET	ET	ET	ET	ET	ET	ET	ET	ET	**T ou ET**
Saison	Saison	Saison	Saison	Saison	Saison	Saison	Saison	Saison	Saison	**Période**
april-november	april-november	april-november	april-november	april-november	april-november	april-november	april-november	april-november	october-february	**Note.période**
water balance	water balance	water balance	water balance	water balance	water balance	water balance	water balance	water balance	water balance	**Méthode**
4,35	4,35	4,35	4,35	4,35	4,35	4,35	4,35	4,35	2,20	**Densité**
Lysimeter	Lysimeter	Lysimeter	Lysimeter	Lysimeter	Lysimeter	Lysimeter	Lysimeter	Lysimeter	Lysimeter	**Contexte**
1	2	2	2	2	2	2	2	2	1	**tiges**
1	3	3	3	3	3	3	3	3	1	**racines**
Sand	Sand	Sand	Clay	Clay	Clay	Clay	Clay	Clay	Sand	**Sol**
sandy loam	sandy loam	sandy loam	Cultivated + fertilized	Cultivated + fertilized	Cultivated	Cultivated	Compacted	Compacted	loamy sand	**Notes.sol**
High	High	High	High	Medium	Medium	Low	Low	Low	High	**Irrigation**
well watered	field capacity	Stressed	field capacity	Stressed	field capacity	Stressed	field capacity	Stressed	NA	**Notes.Irri.**
NA	28,69	16,25	13,90	10,42	8,52	4,37	3,59	2,91	NA	**mm/d**
yes	yes	yes	yes	yes	yes	yes	no	no	no	**Fertilisation**
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**Notes.fert.**
no	no	no	no	no	no	no	no	no	no	**Contamitation**
NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	**Notes.cont.**
United-Kingdom	United-Kingdom	United-Kingdom	United-Kingdom	United-Kingdom	United-Kingdom	United-Kingdom	United-Kingdom	United-Kingdom	New-Zeland	**Pays**

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Martin	2006	S.viminalis	Jorr	1,83	ET	Saison	april-november	water balance	4,35	Lysimeter	1	1	Clay	Compacted	Low	well watered	NA	no	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	2,24	ET	Saison	april-november	water balance	4,35	Lysimeter	1	1	Clay	Cultivated	Low	well watered	nA	no	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	4,03	ET	Saison	april-november	water balance	4,35	Lysimeter	1	1	Clay	Cultivated + fertilized	Medium	well watered	NA	yes	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	10,53	ET	Saison	april-november	water balance	4,35	Lysimeter	1	2	Clay	Cultivated + fertilized	High	field capacity	NA	yes	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	19,45	ET	Saison	april-november	water balance	4,35	Lysimeter	1	2	Sand	sandy loam	High	field capacity	NA	yes	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	17,48	ET	Saison	april-november	water balance	4,35	Lysimeter	1	2	Sand	sandy loam	High	Stressed	NA	yes	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	3,70	ET	Saison	april-november	water balance	4,35	Lysimeter	1	2	Clay	Compacted	Low	field capacity	NA	no	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	3,36	ET	Saison	april-november	water balance	4,35	Lysimeter	1	2	Clay	Compacted	Low	Stressed	NA	no	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	3,81	ET	Saison	april-november	water balance	4,35	Lysimeter	1	2	Clay	Cultivated	Low	Stressed	NA	no	NA	no	NA	United-Kingdom
Martin	2006	S.viminalis	Jorr	4,03	ET	Saison	april-november	water balance	4,35	Lysimeter	1	2	Clay	Cultivated	Medium	field capacity	NA	no	NA	no	NA	United-Kingdom

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Martin	2006	S.viminalis	Jorr	9,52	ET	Saison	april-november	water balance	4,35	Lysimeter	1	2	Clay	Cultivated + fertilized	Medium	Stressed	NA	yes	NA	no	NA	United-Kingdom
Marttila	2018	S.fragilis		0,74	T	Annuelle		Modelisation	uk	Floodplain	UK	UK	Gravel		High			no		no		New-Zeland
Mata-Gonzalez	2014	S.exigua	NA	0,70	ET	Saison	June-August	Modelisation	0,69	Plantation	6	6	Sand	loamy sand	Low	13mm/month	0,43	no	NA	no	NA	United-States
Mata-Gonzalez	2014	S.exigua	NA	0,80	ET	Saison	June-August	Modelisation	0,69	Plantation	6	6	Sand	loamy sand	Medium	26mm/month	0,87	no	NA	no	NA	United-States
Mata-Gonzalez	2014	S.exigua	NA	1,55	ET	Saison	June-August	Modelisation	0,69	Plantation	6	6	Sand	loamy sand	High	39mm/month	1,30	no	NA	no	NA	United-States
Mirck	2009	S.miyabeana	SX64	2,54	T	Saison	33 april-15 november	Sapflow	7,50	Plantation	2	2	other	biosolids	Low	Rain only	0,38	no	NA	no	NA	United-States
Mirck	2009	S.purpurea	9882-34	2,63	T	Saison	30 april-15 november	Sapflow	7,50	Plantation	2	2	other	biosolids	Low	Rain only	0,38	no	NA	no	NA	United-States
Mirck	2009	S.sachalinensis	SX61	2,48	T	Saison	32 april-15 november	Sapflow	7,50	Plantation	2	2	other	biosolids	Low	Rain only	0,38	no	NA	no	NA	United-States
Mirck	2009	S.sachalinensis xS.miyabeana	9870-23	2,68	T	Saison	31 april-15 november	Sapflow	7,50	Plantation	2	2	other	biosolids	Low	Rain only	0,38	no	NA	no	NA	United-States

Peng	Pauliokunis	Nagler	Mirck	Mirck	Mirck	Mirck	Mirck	Mirck	**1er auteur**
2015	2001	2003	2010	2010	2010	2010	2010	2010	**Année**
S.matsudana	S.Babylonica	S.Gooddingii	S.sachalinensis	S.sachalinensis	S.purpurea	S.purpurea	S.miyabeana	S.miyabeana	**Espèce**
NA	NA	NA	9870-40	9870-40	9882-34	9882-34	SX64	SX64	**Variété**
1,85	16,35	12,90	3,20	4,20	3,10	3,80	2,70	3,19	**Résultat**
T	ET	T	ET	ET	ET	ET	ET	ET	**T ou ET**
Saison	Périodique	Périodique	Périodique	Périodique	Périodique	Périodique	Périodique	Périodique	**Période**
may-october	25june-15 august	22 aug.-1 sept.	19sept-28nov	19sept-28nov	19sept-28nov	19sept-28nov	19sept-28nov	19sept-28nov	**Note.période**
Sapflow	water balance	Sapflow	water balance	water balance	water balance	water balance	water balance	water balance	**Méthode**
UK	6,25	5,00	0,10	0,10	0,10	0,10	0,10	0,10	**Densité**
Plantation	Lysimeter	Lysimeter	Pot	Pot	Pot	Pot	Pot	Pot	**Contexte**
20	UK	2	1	1	1	1	1	1	**tiges**
20	UK	2	1	1	1	1	1	1	**racines**
Sand	Clay	Sand	organic	organic	organic	organic	organic	organic	**Sol**
sandy loess	Natural soil + potting mix	Sand + potting mix							**Notes.sol**
Low	High	High	medium	medium	medium	medium	medium	medium	**Irrigation**
Rain only	NA	Constantly moist soil							**Notes.Irri.**
2,59	NA	NA	5,40	5,40	5,40	5,40	5,40	5,40	**mm/d**
no	no	no	no	no	no	no	no	no	**Fertilisation**
NA	NA	NA							**Notes.fert.**
no	no	no	yes	no	yes	no	yes	no	**Contamitation**
NA	NA	NA							**Notes.cont.**
China	United-States	United-States	USA	USA	USA	USA	USA	USA	**Pays**

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Peng	2015	S.matsudana	NA	1,20	T	Saison	may-october	Sapflow	UK	Plantation	20	20	Sand	NA	Low	Rain only	2,59	no	NA	no	NA	China
Peng	2015	S.matsudana	NA	5,29	T	Saison	may-october	Sapflow	UK	Plantation	20	20	Sand	sandy loess	Low	Rain only	3,48	no	NA	no	NA	China
Peng	2015	S.matsudana	NA	3,08	T	Saison	may-october	Sapflow	UK	Plantation	20	20	Sand	NA	Low	Rain only	3,48	no	NA	no	NA	China
Personn	1995	S.viminalis	77082, 77683	3,07	ET	Saison	215	Modelisation	3,00	Plantation	2	2	other	humified organic	Low	Rain only	2,18	yes	solid fertiliser	no	NA	Sweden
Personn	1995	S.viminalis	77082, 77683	3,20	ET	Saison	215	Modelisation	3,00	Plantation	3	3	other	humified organic deposit	Low	Rain only	2,18	yes	solid fertiliser	no	NA	Sweden
Personn	1995	S.viminalis	77082, 77683, 77083	2,49	ET	Saison	215	Modelisation	4,00	Plantation	2	2	Sand	glacial loamy sand	Low	Rain only	2,18	yes	solid fertiliser	no	NA	Sweden
Personn	1995	S.viminalis	77082, 77683, 77083	2,20	ET	Saison	215	Modelisation	4,00	Plantation	3	3	Sand	glacial loamy sand	Low	Rain only	2,18	yes	solid fertiliser	no	NA	Sweden
Personn	1995	S.viminalis	77082, 77683, 77077	2,25	ET	Saison	242	Modelisation	2,70	Plantation	3	6	Sand	fine sand	Low	Rain only	2,75	yes	solid fertiliser	no	NA	Sweden
Personn	1995	S.viminalis	77683	1,53	ET	Saison	242	Modelisation	2,90	Plantation	2	7	Clay	silty clay loam	Low	Rain only	2,86	yes	solid fertiliser	no	NA	Sweden

Ruth	Royygard	Priban	Pistocchi	Pistocchi	Personn	Personn	Personn	Personn	**1er auteur**
2007	1999	1986	2009	2009	1997	1997	1995	1995	**Année**
S.viminalis	S.kinuyanagi	S.cinerea	S.alba	S.alba	S.viminalis	S.viminalis	S.viminalis	S.viminalis	**Espèce**
regalis			SI62-059	SI62-059	NA	NA	82007, 77075	82007, 77075	**Variété**
1,11	4,59	3,03	6,96	4,60	2,30	1,60	2,31	2,02	**Résultat**
ET	ET	ET	ET	ET	ET	ET	ET	ET	**T ou ET**
Annuelle	Saison	Saison	Saison	Saison	Saison	Saison	Saison	Saison	**Période**
NA	summer	july-september	132 jours	132 jours	april-october	april-october	242	242	**Note.période**
Modelisation	water balance	Modelisation	water balance	water balance	Modelisation	Modelisation	Modelisation	Modelisation	**Méthode**
UK	0,39	high	1,89	1,89	UK	UK	3,60	3,60	**Densité**
Plantation	Lysimeter	Floodplain	Lysimeter	Lysimeter	Plantation	Plantation	Plantation	Plantation	**Contexte**
NA	2	UK	1	1	2	2	1	2	**tiges**
NA	3	UK	4	4	UK	UK	5	6	**racines**
other	Sand	Clay	other	other	Clay	Clay	Sand	Sand	**Sol**
mechanical-biological	Manawatu fine sandy		sandy loam	sandy loam	heavy clay	heavy clay	fine sand	fine sand	**Notes.sol**
Low	High	High	Medium	Medium	Low	Low	Low	Low	**Irrigation**
Rain only	Rain + irrigation	partially flooded	Rain + irrigation	Rain + irrigation	rain, humid climate	rain, dry climate	Rain + irrigation	Rain + irrigation	**Notes.Irri.**
1,39	NA	NA	NA	NA	2,47	1,30	3,92	2,97	**mm/d**
yes	yes	no	yes	yes	no	no	yes	yes	**Fertilisation**
substrate	dairy effluent	NA	high	low	NA	NA	liquid fertilizer	liquid fertilizer	**Notes.fert.**
no	yes	no	no	no	no	no	no	no	**Contamitation**
NA	dairy effluent (cl)	NA	NA	NA	NA	NA	NA	NA	**Notes.cont.**
Germany	New-Zeland	Czechoslovakia	Italy	Italy	Sweden	Sweden	Sweden	Sweden	**Pays**

Stephens	Stephens	Schmidt-Walter	Schmidt-Walter	Scheirlink	Ruth	Ruth	Ruth	Ruth	Ruth	**1er auteur**
2001	2000	2012	2012	1996	2007	2007	2007	2007	2007	**Année**
S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	S.viminalis	**Espèce**
Q683	**Q683**	Tora	Tora		regalis	regalis	regalis	regalis	regalis	**Variété**
1,78	**3,39**	1,27	1,47	1,15	1,07	1,16	1,21	1,00	1,08	**Résultat**
ET	ET	ET	ET	T	ET	ET	ET	ET	ET	**T ou ET**
Ponctuelle	Ponctuelle	Annuelle	Annuelle	Saison	Annuelle	Annuelle	Annuelle	Annuelle	Annuelle	**Période**
26 jours	26 jours	NA	NA	200 days	NA	NA	NA	NA	NA	**Note.période**
water balance	water balance	Modelisation	Modelisation	Modelisation	Modelisation	Modelisation	Modelisation	Modelisation	Modelisation	**Méthode**
20,38	20,38	UK	UK	UK	UK	UK	UK	UK	UK	**Densité**
Pot	Pot	Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	Plantation	**Contexte**
1	1	6	1	1	NA	NA	NA	NA	NA	**tiges**
1	1	6	7	1	NA	NA	NA	NA	NA	**racines**
sand	sand	Clay	Clay	other	Sand	other	other	Sand	other	**Sol**
sandy loam	sandy loam	agricultural site	agricultural site	sludge	loamy sand	compost	mechanical-biological	loamy sand	compost	**Notes.sol**
high	high	Low	Low	Low	Low	Low	Low	Low	Low	**Irrigation**
toujours plein	toujours plein	Rain only	Rain only	Rain only	Rain only	Rain only	Rain only	Rain only	Rain only	**Notes.Irri.**
NA	NA	1,10	0,68	1,05	1,72	1,72	1,72	1,39	1,39	**mm/d**
no	no	no	no	yes	no	yes	yes	no	yes	**Fertilisation**
NA	NA	NA	NA	NA	NA	substrate	substrate	NA	substrate	**Notes.fert.**
yes	no	no	no	yes	no	no	no	no	no	**Contamitation**
chloride, 352 mmol/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	**Notes.cont.**
United-Kingdom	United-Kingdom	Germany	Germany	Belgium	Germany	Germany	Germany	Germany	Germany	**Pays**

1er auteur	Année	Espèce	Variété	Résultat	T ou ET	Période	Note.période	Méthode	Densité	Contexte	tiges	racines	Sol	Notes.sol	Irrigation	Notes.Irri.	mm/d	Fertilisation	Notes.fert.	Contamitation	Notes.cont.	Pays
Tallis	2013	S.viminalis	Joruun	2,50	T	Périodique	july-august	Modelisation	1,00	Plantation	3	UK	other	loam	Low	Rain only	2,35	no	NA	no	NA	United-Kingdom
Tang	2018	S.caroliana		3,75	ET	Annuelle		Modelisation	UK	Floodplain	old	old	na		High			no		no		USA
Tang	2018	S.caroliana		2,83	ET	Annuelle		Modelisation	UK	Floodplain	old	old	na		high			no		yes		USA
Wang	2015	S.matsudana		2,11	ET	Périodique	64 days	Sapflow	low	Plantation	30	30	Sand	aeolian sandy soil	Low	severe water stress	2,56	no	NA	no	NA	China
Wang	2019	S.matsudana		1,75	t	saison	may1-OCT15	sapflow		plantation	old	old	sand		low		2,65	no		no		China
Yin	2014	S.matsudana		6,27	ET	Saison	201 days	Sapflow	0,16	Plantation	44	44	Sand	aeolian sandy soil	Low	semi-arid	0,94	no	NA	no	NA	China

Annexe 4 | Résultats détaillés des analyses réalisées à différents point d'échantillonnage du système de traitement des lixiviats mis en place sur un site d'entreposage de poteaux traités

Tableau 1 : Résultats analytiques des échantillons d'eau prélevés le 16 mars 2016 en fonction des critères du Règlement numéro 2008-47 de la CMM

Paramètres	Unités	Norme de la CMM[1]	Échantillons									
			OA-2016-03-16 LAV	OAR-2016-03-16 LAV	ET-14-2016-03-16 LAV	ET-14R-2016-03-16 LAV						
Séquence			Amont des systèmes de traitement	Duplicata	Fossé récepteur	Duplicata						
Date d'échantillonnage			16-mars-16	16-mars-16	16-mars-16	16-mars-16						
Dioxines et furannes [2, 3]	pg/l	0,0031	4,2	-	7,4	6,5						
Huiles et graisses totales	mg/l	15	<3,0	-	<3,0	-						
Huiles et graisses minérales	mg/l	15	<3,0	<3,0	<3,0	-						
Métaux												
Aluminium	µg/l	3 000	54	-	1300	-						
Argent	µg/l	120	<0,50	-	<0,50	-						
Arsenic	µg/l	1 000	340	-	<1,0	-						
Baryum	µg/l	1 000	2,1	-	31	-						
Cadmium	µg/l	100	<0,20	-	<0,20	-						
Chrome	µg/l	1 000	37	-	<5,0	-						
Chrome hexavalent	µg/l	40	<8,0	-	<8,0	-						
Cobalt	µg/l	-	<1,0	-	<1,0	-						
Cuivre	µg/l	1 000	91	-	3,4	-						
Étain	µg/l	1 000	<2,0	-	<2,0	-						
Fer	µg/l	15 000	130	-	770	-						
Manganèse	µg/l	100	26	-	18	-						
Molybdène	µg/l	-	1,1	-	<1,0	-						
Mercure	µg/l	1	<0,10	-	<0,10	-						
Nickel	µg/l	1 000	<2,0	-	5,7	-						
Plomb	µg/l	100	<0,50	-	0,7	-						
Sélénium	µg/l	20	3,9	-	<3,0	-						
Zinc	µg/l	1 000	200	-	11	-						
Inorganiques												
COT	mg/l	-	9	-	2	-						
DCO	mg/l- O2	60	75	-	15	-						
MES	mg/l	30	5	-	19	-						
pH	pH	6 à 9,5	6,15	-	7,39	-						
Phénols totaux	mg/l	0,02	0,004	-	0,002	<0,002						
Composés phénoliques												
2,4-diméthylphénol	µg/l	-	<0,6	-	<0,6	-						
2,4-Dinitrophénol	µg/l	-	<10	-	<10	-						
2-Méthyl-4,6-dinitrophénol	µg/l	-	<10	-	<10	-						
4-nitrophénol	µg/l	-	<2	-	<1	-						
Phénol	µg/l	-	0,9	-	<0,6	-						
2-chlorophénol	µg/l	-	<0,5	-	<0,5	-						
3-chlorophénol	µg/l	-	<0,5	-	<0,5	-						
4-chlorophénol	µg/l	-	<0,4	-	<0,4	-						
2,3-dichlorophénol	µg/l	-	<0,5	-	<0,5	-						
2,4 + 2,5-dichlorophénol	µg/l	-	<0,3	-	<0,3	-						
2,6-dichlorophénol	µg/l	-	<0,4	-	<0,4	-						
3,4-dichlorophénol	µg/l	-	<0,4	-	<0,4	-						
3,5-dichlorophénol	µg/l	-	<0,4	-	<0,4	-						
Pentachlorophénol	µg/l	60	3,2	-	<0,4	-						
2,3,4,6-tétrachlorophénol	µg/l	-	<0,4	-	<0,4	-						
2,3,5,6-tétrachlorophénol	µg/l	-	<0,4	-	<0,4	-						
2,4,5-trichlorophénol	µg/l	-	<0,4	-	<0,4	-						
2,4,6-trichlorophénol	µg/l	-	<0,4	-	<0,4	-						
2,3,5-Trichlorophénol	µg/l	-	<0,4	-	<0,4	-						
2,3,4-Trichlorophénol	µg/l	-	<0,4	-	<0,4	-						
2,3,6-Trichlorophénol	µg/l	-	<0,4	-	<0,4	-						
2,3,4,5-Tétrachlorophénol	µg/l	-	<0,4	-	<0,4	-						
3,4,5-Trichlorophénol	µg/l	-	<0,4	-	<0,4	-						
ortho-Crésol	µg/l	-	<1	-	<1	-						
para-Crésol	µg/l	-	<1	-	<1	-						
Couleur observée	-	-	Clair	-	Beige	-						
Matières présentes	-	-	-	-	-	-						
Odeur	-	-	-	-	-	-						
Pluviométrie	mm	-	-	-	-	-						
Température	°C	45	4,02	-	2,2	-						

- signifie: pas de critère défini pour ce paramètre ou non analysé.

[1] Règlement numéro 2008-47 sur l'assainissement des eaux de la CMM - Annexe 1, Colonne C : Valeurs applicables aux déversements dans les réseaux d'égout pluviaux ou dans les cours d'eau.

[2] Les résultats sont exprimés en équivalence toxique totale, échelle de l'OMS.

[3] Critères de la qualité de l'eau de surface au Québec, critère de protection de la faune terrestre piscivore.

Tableau 2 : Résultats analytiques des échantillons d'eau prélevés entre le 7 juin et le 27 juin 2016 en fonction des critères du Règlement numéro 2008-47 de la CMM

Paramètres	**Unités**	**Norme de la CMM[1]**	**Échantillons**															
			EB-2-2016-06-07-LAV	EB-2R-2016-06-07-LAV	ET-4A-2016-06-13-LAV	ET-4R-2016-06-13-LAV	ET-6-2016-06-13-LAV	ET-6R-2016-06-13-LAV	R-6-2016-06-20-LAV	R-6R-2016-06-20-LAV	ET-7K-2016-06-27-LAV	ET-7KR-2016-06-27-LAV	ET-12-2016-06-22-LAV	ET-12R-2016-06-22-LAV	ET-13-2016-06-27-LAV	ET-13R-2016-06-27-LAV		
Séquence			Amont des systèmes de traitement	Duplicata	Aval unité Stantec	Duplicata	Aval unité HG	Duplicata	Aval unité IRBV	Duplicata	Aval unité Polytechnique	Duplicata	Amont des Saules	Duplicata	Aval des unités de traitements	Duplicata		
Date d'échantillonnage			07-juin-16	07-juin-16	13-juin-16	13-juin-16	13-juin-16	13-juin-16	20-juin-16	20-juin-16	27-juin-16	27-juin-16	22-juin-16	22-juin-16	27-juin-16	27-juin-16		
Dioxines et furannes [2, 3]	pg/l	0,0031	140	150	2,4	-	0,0015	-	4,8	-	0	-	0,43	-	0,0013	-		
HAP																		
Benzo(a)anthracène	µg/L	-	<0,03	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Benzo (b) fluoranthène	µg/L	-	<0,06	-	-	-	-	-	-	-	-	-	<0,1	-	<0,06	<0,06		
Benzo (j) fluoranthène	µg/L	-	<0,06	-	-	-	-	-	-	-	-	-	<0,1	-	<0,06	<0,06		
Benzo (k) fluoranthène	µg/L	-	<0,06	-	-	-	-	-	-	-	-	-	<0,1	-	<0,06	<0,06		
Benzo (a) pyrène	µg/L	-	<0,008	-	-	-	-	-	-	-	-	-	<0,1	-	<0,008	<0,008		
Chrysène	µg/L	-	0,03	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Dibenzo (a,h) anthracène	µg/L	-	<0,03	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Dibenzo (a,i) pyrène	µg/L	-	<0,1	-	-	-	-	-	-	-	-	-	<0,1	-	-	-		
Indéno (1,2,3-cd) pyrène	µg/L	-	<0,03	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Sommation des HAP [4]	µg/L	1	<0,1	-	-	-	-	-	-	-	-	-	<0,1	-	-	-		
Acénaphtène	µg/L	-	0,07	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Anthracène	µg/L	-	0,04	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Benzo (g,h,i) pérylène	µg/L	-	<0,1	-	-	-	-	-	-	-	-	-	<0,1	-	-	-		
Benzo (e) pyrène	µg/L	-	<0,1	-	-	-	-	-	-	-	-	-	<0,1	-	-	-		
Fluoranthène	µg/L	1	0,17	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Fluorène	µg/L	-	0,11	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Naphtalène	µg/L	150	<0,03	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Phénanthrène	µg/L	63	0,15	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Pyrène	µg/L	-	0,14	-	-	-	-	-	-	-	-	-	<0,1	-	<0,03	<0,03		
Sommation des HAP [5]	µg/L	200	0,7	-	-	-	-	-	-	-	-	-	<0,1	-	-	-		
Hydrocarbures pétroliers C_{10} à C_{50}	µg/L	2800	-	-	-	-	-	-	-	-	-	-	<100	-	-	-		
Huiles et graisses totales	mg/l	15	<3,0	-	-	-	-	-	-	-	-	-	<3,0	<3,0	<3,0	-		
Huiles et graisses minérales	mg/l	15	<3,0	-	-	-	-	-	-	-	-	-	<3,0	<3,0	<3,0	-		
Métaux																		
Aluminium	µg/l	3 000	63	-	45	45	39	-	<10	13	10	-	16	-	15	-		
Argent	µg/l	120	<1.0	-	<1,0	<1,0	<1,0	-	<1,0	<1,0	<1,0	-	<1,0	-	<1,0	-		
Arsenic	µg/l	1 000	470	-	540	550	42	-	200	210	7,6	-	68	-	16	-		
Baryum	µg/l	1 000	10	-	22	22	23	-	100	100	110	-	55	-	73	-		
Cadmium	µg/l	100	0.20	-	<0,20	<0,20	<0,20	-	<0,20	<0,20	<0,20	-	<0,20	-	<0,20	-		
Chrome	µg/l	1 000	160	-	81	83	6,7	-	21	23	<5,0	-	10	-	<5,0	-		
Chrome hexavalent	µg/l	40	<8	-	<8	<8	<8	-	<8		<8	-	<8	-	<8	-		
Cobalt	µg/l	-	<1.0	-	4,3	4,3	2	-	6	6,6	<1,0	-	1,2	-	4,1	-		
Cuivre	µg/l	1 000	520	-	54	54	2,4	-	110	120	<1,0	-	25	-	<1,0	-		
Étain	µg/l	1 000	<2.0	-	<2,0	<2,0	<2,0	-	<2,0	<2,0	<2,0	-	3	-	<2,0	-		
Fer	µg/l	15 000	630	-	5100	5200	3300	-	3500	3600	3000	-	1500	-	2100	-		
Manganèse	µg/l	100	110	-	2000	2000	160	-	680	710	360	-	250	-	590	-		
Molybdène	µg/l	-	1.1	-	<1,0	<1,0	15	-	22	22	23	-	14	-	19	-		
Mercure	µg/l	1	<0.10	-	<0,10	0,11	<0,10	-	<0,10	<0,10	<0,10	-	<0,10	-	<0,10	-		
Nickel	µg/l	1 000	<2.0	-	2,8	3,2	38	-	26	28	3,9	-	15	-	4,1	-		
Phosphore total	µg/l	400	59	-	550	-	35	-	-	-	51	-	48	-	42	-		
Plomb	µg/l	100	0.67	-	<0,50	0,52	<0,50	-	0,59	0,74	<0,50	-	<0,50	-	<0,50	-		
Potassium	µg/l	-	3500	-	-	-	-	-	-	-	4200	-	3600	-	5100	-		
Sélénium	µg/l	20	9.7	-	<3,0	<3,0	<3,0	-	<3,0	<3,0	<3,0	-	<3,0	-	<3,0	-		
Zinc	µg/l	1 000	140	-	27	27	<7,0	-	11	16	9	-	<7,0	-	12	-		
Inorganiques																		
Azote ammoniacal [6]	mg/l	12	0,06	-	-	-	-	-	-	-	-	-	0,08	-	0,12	-		
COT	mg/l	-	100	-	47	-	5,5	-	41,3	-	17	-	26,9	-	42,8	-		
DCO	mg/l- O2	60	310	-	140	-	59	60	100	100	45	-	41	-	45	-		
Fluorure	mg/l	2	<0,1 (*)	-	<0,1	-	0,1	-	0,1	-	0,2	-	0,1	-	0,1	0,1		
MES	mg/l	30	33	-	29	-	11	-	12	-	10	10	16	-	16	-		
pH	pH	6 à 9,5	6,88	-	7,12	-	7,15	-	7,21	-	7,24	-	7,69		7,12	-		
Nitrate et Nitrite	mg/l	-	<0,02	<0,02	<0,02	-	-	-	-	-	<0,02	-	<0,2	-	<0,02	<0,02		
Sulfures	mg/l	1	0,7	-	0,07	-	0,11	-	0,03	-	0,08	-	0,02	<0,02	<0,02	-		
Phénols totaux	mg/l	0,02	-	-	-	-	-	-	-	-	-	-	-	-	<0,002	-		
Composés phénoliques																		
2,4-diméthylphénol	µg/l	-	<0.6	<0.6	<0,6	-	<0,6	-	<0,6	-	<0,6	-	<1	-	<0,6	-		
2,4-Dinitrophénol	µg/l	-	<10	<10	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-		
2-Méthyl-4,6-dinitrophénol	µg/l	-	<10	<10	<10	-	<10	-	<10	-	<10	-	<10	-	<10	-		
4-nitrophénol	µg/l	-	<3 (7)	<1	<1	-	<1	-	<1	-	<1	-	<1	-	<1	-		
Phénol	µg/l	-	2.5	2.3	0,7	-	<0,6	-	2,6	-	<0,6	-	<1	-	<0,6	-		
2-chlorophénol	µg/l	-	<0.5	<0.5	<0,5	-	<0,5	-	<0,5	-	<0,5	-	<1	-	<0,5	-		
3-chlorophénol	µg/l	-	<0.5	<0.5	<0,5	-	<0,5	-	<0,5	-	<0,5	-	<1	-	<0,5	-		
4-chlorophénol	µg/l	-	<0.4	<0.4	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
2,3-dichlorophénol	µg/l	-	<0.5	<0.5	<0,5	-	<0,5	-	<0,5	-	<0,5	-	<1	-	<0,5	-		
2,4 + 2,5-dichlorophénol	µg/l	-	<0.3	<0.3	<0,3	-	<0,3	-	<0,3	-	<0,3	-	<1	-	<0,3	-		
2,6-dichlorophénol	µg/l	-	<0.4	<0.4	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
3,4-dichlorophénol	µg/l	-	<0.4	<0.4	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
3,5-dichlorophénol	µg/l	-	0.6	0.7	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
Pentachlorophénol	µg/l	60	11	12	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
2,3,4,6-tétrachlorophénol	µg/l	-	1.3	1.3	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
2,3,5,6-tétrachlorophénol	µg/l	-	1.3	1.2	0,9	-	0,4	-	0,4	-	<0,4	-	<1	-	<0,4	-		
2,4,5-trichlorophénol	µg/l	-	<0.4	<0.4	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
2,4,6-trichlorophénol	µg/l	-	<0.4	<0.4	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
2,3,5-Trichlorophénol	µg/l	-	<0.4	<0.4	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
2,3,4-Trichlorophénol	µg/l	-	<0.4	<0.4	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
2,3,6-Trichlorophénol	µg/l	-	<0.4	<0.4	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
2,3,4,5-Tétrachlorophénol	µg/l	-	0.5	0.5	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
3,4,5-Trichlorophénol	µg/l	-	0.6	0.8	<0,4	-	<0,4	-	<0,4	-	<0,4	-	<1	-	<0,4	-		
ortho-Crésol	µg/l	-	<1	<1	<1	-	<1	-	<1	-	<1	-	<1	-	<1	-		
para-Crésol	µg/l	-	13	14	9	-	<1	-	10	-	<1	-	<1	-	<1	-		
Couleur observée	-	-	Beige	-	Brunâtre	-	Jaunâtre	-		-		-		-		-		
Matières présentes	-	-	Légère	-	Aucune	-	Aucune	-		-		-		-		-		
Odeur	-	-	Sulfure	-	Aucune	-	Aucune	-		-		-		-		-		
Pluviométrie	mm	-	-	-	-	-	-	-		-		-		-		-		
Température	°C	45	9,55	-	8,3	-	7,85	-		-		-		-		-		

- signifie: pas de critère défini pour ce paramètre ou non analysé.

[1] Règlement numéro 2008-47 sur l'assainissement des eaux de la CMM - Annexe 1, Colonne C : Valeurs applicables aux déversements dans les réseaux d'égout pluviaux ou dans les cours d'eau.

[2] Les résultats sont exprimés en équivalence toxique totale, échelle de l'OMS.

[3] Critères de la qualité de l'eau de surface au Québec, critère de protection de la faune terrestre piscivore.

[4] Somme des concentrations des HAP suivants : Benzo(a)anthracène, Benzo (b) fluoranthène, Benzo (j) fluoranthène, Benzo (k) fluoranthène, Benzo (a) pyrène, Chrysène, Dibenzo (a,h) anthracène, Dibenzo (a,i) pyrène et Indéno (1,2,3-cd) pyrène.

[5] Somme des concentrations des HAP suivants : Acénaphtène, Anthracène, Benzo (g,h,i) pérylène, Benzo (e) pyrène, Fluoranthène, Fluorène, Naphtalène, Phénanthrène et Pyrène.

[6] 12 mg/L si pH ≤7,56 mg/L si 7,5<pH≤8,02 mg/L si 8,0<pH≤8,50,7 mg/L si 8,5<pH

[7] Dû à l'interférence de la matrice, la limite de détection a été augmentée.

(*) Le résultat est celui de l'échantillon prélevé en duplicata

Tableau 3 : Résultats analytiques des échantillons d'eau prélevés entre le 26 août et le 14 septembre 2016 en fonction des critères du Règlement numéro 2008-47 de la CMM

Paramètres	Unités	Norme de la CMM[1]	Échantillons															
			EB-2-2016-08-26-LAV	EB-2R-2016-08-26-LAV	ET-4A-2016-09-01-LAV	ET-4AR-2016-09-01-LAV	ET-6-2016-08-30-LAV	ET-6R-2016-08-30-LAV	R-6-2016-09-06-LAV	R-6R-2016-09-06-LAV	ET-7K-2016-09-14-LAV	ET-7KR-2016-09-14-LAV	ET-12-2016-09-06-LAV	ET-12R-2016-09-06-LAV	ET-13-2016-09-08-LAV	ET-13R-2016-09-08-LAV		
Séquence			Amont des systèmes de traitement	Duplicata	Aval unité Stantec	Duplicata	Aval unité HG	Duplicata	Aval unité IRBV	Duplicata	Aval unité Polytechnique	Duplicata	Amont des Saules	Duplicata	Aval des unités de traitements	Duplicata		
Date d'échantillonnage			26-août-16	26-août-16	01-sept-16	01-sept-16	30-août-16	30-août-16	06-sept-16	06-sept-16	14-sept-16	14-sept-16	06-sept-16	06-sept-16	08-sept-16	08-sept-16		
Dioxines et furannes [2, 3]	pg/l	0,0031	98		0,026	-	0,0069	-	1,2	-		-	0,28	-	0,011	-		
HAP																		
Benzo(a)anthracène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (b) fluoranthène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (j) fluoranthène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (k) fluoranthène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (a) pyrène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Chrysène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Dibenzo (a,h) anthracène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Dibenzo (a,i) pyrène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Indéno (1,2,3-cd) pyrène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Sommation des HAP [4]	µg/L	1	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Acénaphtène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Anthracène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (g,h,i) pérylène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (e) pyrène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Fluoranthène	µg/L	1	0,1	0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Fluorène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Naphtalène	µg/L	150	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Phénanthrène	µg/L	63	<0,1	0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Pyrène	µg/L	-	<0,1	<0,1	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Sommation des HAP [5]	µg/L	200	0,1	0,2	-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Hydrocarbures pétroliers C_{10} à C_{50}	µg/L	2800	-	-	-	-	-	-	-	-	-	-	-	-	-	-		
Huiles et graisses totales	mg/l	15	<3,0	-	-	-	-	-	-	-	-	-	<3,0	-	<3,0	<3,0		
Huiles et graisses minérales	mg/l	15	<3,0	-	-	-	-	-	-	-	-	-	<3,0	-	<3,0	<3,0		
Métaux																		
Aluminium	µg/l	3 000	21	-	33	-	41	-	17	-	<10	-	20	21	15	-		
Argent	µg/l	120	<1,0	-	1,6	-	<1,0	-	<1,0	-	<1,0	-	<1,0	<1,0	<1,0	-		
Arsenic	µg/l	1 000	1100	-	140	-	55	-	180	-	11	-	80	82	60	-		
Baryum	µg/l	1 000	10	-	11	-	32	-	66	-	79	-	44	44	67	-		
Cadmium	µg/l	100	<0,20	-	<0,20	-	<0,20	-	<0,20	-	<0,20	-	<0,20	<0,20	<0,20	-		
Chrome	µg/l	1 000	70	-	14	-	<5,0	-	15	-	<5,0	-	8,3	9	<5,0	-		
Chrome hexavalent	µg/l	40	<8	-	<8	-	8	-	<8	-	<8	-	<8	<8	<8	-		
Cobalt	µg/l	-	<1,0	-	<1,0	-	<1,0	-	1,5	-	<1,0	-	<1,0	<1,0	2,9	-		
Cuivre	µg/l	1 000	240	-	21	-	<1,0	-	32	-	<1,0	-	14	15	<1,0			
Étain	µg/l	1 000	<2,0	-	<2,0	-	9,8	-	<2,0	-	<2,0	-	<2,0	<2,0	<2,0	-		
Fer	µg/l	15 000	490	-	<60	-	5400	-	4200	-	2500	-	1600	1600	4600	-		
Manganèse	µg/l	100	74	-	1	-	310	-	660	-	260	-	240	240	730	-		
Molybdène	µg/l	-	2,4	-	<1,0	-	5,5	-	13	-	18	-	7,9	8,4	18	-		
Mercure	µg/l	1	0,25	-	<0,10	-	<0,10	-	<0,10	-	0,11	-	<0,10	<0,10	0,19	-		
Nickel	µg/l	1 000	<2,0	-	2,3	-	13	-	6,9	-	2,1	-	5,4	5,5	4,6	-		
Phosphore total	µg/l	400	95	-	110	110	<10	-	28	-	45	-	44	-	73	-		
Plomb	µg/l	100	0,57	-	<0,50	-	<0,50	-	<0,50	-	<0,50	-	<0,50	<0,50	<0,50	-		
Potassium	µg/l	-	3200	-	-	-	-	-	-	-	-	-	3400	-	4000	-		
Sélénium	µg/l	20	4,8	-	<3,0	-	<3,0	-	<3,0	-	<3,0	-	<3,0	<3,0	<3,0	-		
Zinc	µg/l	1 000	100	-	18	-	<7,0	-	<7,0	-	<7,0	-	8,3	<7,0	<7,0	-		
Inorganiques																		
Azote ammoniacal [6]	mg/l	12			-	-	-	-	-	-	-	-	0,04	-	0,11	-		
COT	mg/l	-	17	-	8,4	-	-	-	15	-	16	-	17	-	16	-		
DCO	mg/l- O2	60	110	-	30	-	55	-	67	-	54	-	40	43	54	-		
Fluorure	mg/l	2	0,1	-	0,1	-	0,2	-	0,1	-	0,3	-	0,2	-	0,2	0,2		
MES	mg/l	30	3	-	2	-	2	3	3	-	<2	-	<2	-	<2	-		
pH	pH	6 à 9,5	7,04	-	8,1	-	7,06	-	7,24	-	7,3	7,31	7,58	-	7,45	-		
Nitrate et Nitrite	mg/l	-	<0,2	-	0,2	-	-	-	-	-	-	-	<0,2	-	<0,02	-		
Sulfures	mg/l	1	0,18	-	<0,02	-	0,15	-	0,09	-	0,18	-	<0,02	-	<0,02	-		
Phénols totaux	mg/l	0,02	-	-			-		-	-	-	-	<0,002	-	<0,002	-		
Composés phénoliques																		
2,4-diméthylphénol	µg/l	-		-	<0,6	-	<0,6	-				-		-				
2,4-Dinitrophénol	µg/l	-		-	<10	-	<10	-				-		-				
2-Méthyl-4,6-dinitrophénol	µg/l	-		-	<10	-	<10	-				-		-				
4-nitrophénol	µg/l	-		-	<1	-	<1	-				-		-				
Phénol	µg/l	-		-	<0,6	-	<0,6	-				-		-				
2-chlorophénol	µg/l	-		-	<0,5	-	<0,5	-				-		-				
3-chlorophénol	µg/l	-		-	<0,5		<0,5							-				
4-chlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
2,3-dichlorophénol	µg/l	-		-	<0,5	-	<0,5	-				-		-				
2,4 + 2,5-dichlorophénol	µg/l	-		-	<0,3	-	<0,3	-				-		-				
2,6-dichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
3,4-dichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
3,5-dichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
Pentachlorophénol	µg/l	60		-	<0,4	-	<0,4	-				-		-				
2,3,4,6-tétrachlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
2,3,5,6-tétrachlorophénol	µg/l	-		-	0,4	-	<0,4	-				-						
2,4,5-trichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
2,4,6-trichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
2,3,5-Trichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
2,3,4-Trichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
2,3,6-Trichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
2,3,4,5-Tétrachlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
3,4,5-Trichlorophénol	µg/l	-		-	<0,4	-	<0,4	-				-		-				
ortho-Crésol	µg/l	-		-	<1	-	<1	-				-		-				
para-Crésol	µg/l	-		-	<1	-	<1	-				-		-				
Couleur observée	-	-		-		-		-		-		-		-		-		
Matières présentes	-	-		-		-		-		-		-		-		-		
Odeur	-	-		-		-		-		-		-		-		-		
Pluviométrie	mm	-		-		-		-		-		-		-		-		
Température	°C	45		-		-		-		-		-		-		-		

- signifie: pas de critère défini pour ce paramètre ou non analysé.

[1] Règlement numéro 2008-47 sur l'assainissement des eaux de la CMM - Annexe 1, Colonne C : Valeurs applicables aux déversements dans les réseaux d'égout pluviaux ou dans les cours d'eau.

[2] Les résultats sont exprimés en équivalence toxique totale, échelle de l'OMS.

[3] Critères de la qualité de l'eau de surface au Québec, critère de protection de la faune terrestre piscivore.

[4] Somme des concentrations des HAP suivants : Benzo(a)anthracène, Benzo (b) fluoranthène, Benzo (j) fluoranthène, Benzo (k) fluoranthène, Benzo (a) pyrène, Chrysène, Dibenzo (a,h) anthracène, Dibenzo (a,i) pyrène et Indéno (1,2,3-cd) pyrène.

[5] Somme des concentrations des HAP suivants : Acénaphtène, Anthracène, Benzo (g,h,i) pérylène, Benzo (e) pyrène, Fluoranthène, Fluorène, Naphtalène, Phénanthrène et Pyrène.

[6] 12 mg/L si pH ≤7,56 mg/L si 7,5<pH≤8,02 mg/L si 8,0<pH≤8,50,7 mg/L si 8,5<pH

[7] Dû à l'interférence de la matrice, la limite de détection a été augmentée.

(*) Le résultat est celui de l'échantillon prélevé en duplicata

EnviroServices

Tableau 3 : Résultats analytiques des échantillons d'eau prélevés entre le 26 août et le 14 septembre 2016 en fonction des critères du Règlement numéro 2008-47 de la CMM

Hydro Québec

Paramètres	Unités	Norme de la CMM[1]	Échantillons															
			EB-2-2016-08-26-LAV	EB-2R-2016-08-26-LAV	ET-4A-2016-09-01-LAV	ET-4AR-2016-09-01-LAV	ET-6-2016-08-30-LAV	ET-6R-2016-08-30-LAV	R-6-2016-09-06-LAV	R-6R-2016-09-06-LAV	ET-7K-2016-09-14-LAV	ET-7KR-2016-09-14-LAV	ET-12-2016-09-06-LAV	ET-12R-2016-09-06-LAV	ET-13-2016-09-08-LAV	ET-13R-2016-09-08-LAV		
Séquence			Amont des systèmes de traitement	Duplicata	Aval unité Stantec	Duplicata	Aval unité HG	Duplicata	Aval unité IRBV	Duplicata	Aval unité Polytechnique	Duplicata	Amont des Saules	Duplicata	Aval des unités de traitements	Duplicata		
Date d'échantillonnage			26-août-16	26-août-16	01-sept-16	01-sept-16	30-août-16	30-août-16	06-sept-16	06-sept-16	14-sept-16	14-sept-16	06-sept-16	06-sept-16	08-sept-16	08-sept-16		
Dioxines et furannes[2, 3]	pg/l	0,0031	-		32,2	-	14,77	-	-	-		-	126	-	6,8	-		
HAP																		
Benzo(a)anthracène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (b) fluoranthène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (j) fluoranthène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (k) fluoranthène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (a) pyrène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Chrysène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Dibenzo (a,h) anthracène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Dibenzo (a,i) pyrène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Indéno (1,2,3-cd) pyrène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Sommation des HAP[4]	µg/L	1			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Acénaphtène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Anthracène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (g,h,i) pérylène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Benzo (e) pyrène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Fluoranthène	µg/L	1			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Fluorène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Naphtalène	µg/L	150			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Phénanthrène	µg/L	63			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Pyrène	µg/L	-			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Sommation des HAP[5]	µg/L	200			-	-	-	-	-	-	-	-	<0,1	-	<0.1	-		
Hydrocarbures pétroliers C_{10} à C_{50}	µg/L	2800			-	-	-	-	-	-	-	-	-	-	-	-		
Huiles et graisses totales	mg/l	15			-	-	-	-	-	-	-	-	<3,0	-	<3,0	<3,0		
Huiles et graisses minérales	mg/l	15		-	-	-	-	-	-	-	-	-	<3,0	-	<3,0	<3,0		
Métaux																		
Aluminium	µg/l	3 000		-	18	18	28	-		-		-	40			-		
Argent	µg/l	120		-	<1,0	<1,0	<1,0	-		-		-	<1,0			-		
Arsenic	µg/l	1 000		-	110	110	10	-		-		-	99			-		
Baryum	µg/l	1 000		-	12	12	21	-		-		-	34			-		
Cadmium	µg/l	100		-	<0,20	<0,20	<0,20	-		-		-	<0,20			-		
Chrome	µg/l	1 000		-	22	22	<5,0	-		-		-	14			-		
Chrome hexavalent	µg/l	40		-	<8	<8	<8	-		-		-	<8			-		
Cobalt	µg/l	-		-	<1,0	<1,0	<1,0	-		-		-	<1,0			-		
Cuivre	µg/l	1 000		-	14	13	2,0	-		-		-	13					
Étain	µg/l	1 000		-	<2,0	<2,0	<2,0	-		-		-	<2,0			-		
Fer	µg/l	15 000		-	<60	<60	3400	-		-		-	5400			-		
Manganèse	µg/l	100		-	<1,0	<1,0	160	-		-		-	260			-		
Molybdène	µg/l	-		-	<1,0	<1,0	7,0	-		-		-	6,6			-		
Mercure	µg/l	1		-	<0,10	<0,10	<0,10	-		-		-	<0,10			-		
Nickel	µg/l	1 000		-	<2,0	<2,0	19	-		-		-	7,2			-		
Phosphore total	µg/l	400		-	26	<10	<10	-		-		-	70			-		
Plomb	µg/l	100		-	<0,50	<0,50	<0,50	-		-		-	<0,50			-		
Potassium	µg/l	-		-	N/A	N/A	N/A	-		-		-	4200			-		
Sélénium	µg/l	20		-	<3,0	<3,0	<3,0	-		-		-	<3,0			-		
Zinc	µg/l	1 000		-	<7,0	<7,0	<7,0	-		-		-	13			-		
Inorganiques																		
Azote ammoniacal[6]	mg/l	12			-	-	-	-	-	-		-	-	-	0,11	-		
COT	mg/l	-		-	7	-	9	-		-		-	9.8	-	16	-		
DCO	mg/l- O2	60		-	21	-	30	-		-		-	39	43	54	-		
Fluorure	mg/l	2		-	-	-	-	-		-		-	-	-	0,2	0,2		
MES	mg/l	30		-	4	-	3			-		-	13	-	<2	-		
pH	pH	6 à 9,5		-	8.10	-	7.15	-		-			7.65	-	7,45	-		
Nitrate et Nitrite	mg/l	-		-	0.46	-	<0.02	-		-		-	0.21	-	<0,02	-		
Sulfures	mg/l	1		-	-	-	-	-		-		-	-	-	<0,02	-		
Phénols totaux	mg/l	0,02		-	-		-			-		-	0.002	-	<0,002	-		
Composés phénoliques																		
2,4-diméthylphénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,4-Dinitrophénol	µg/l	-		-	<10	-	<10	-				-	<10	-				
2-Méthyl-4,6-dinitrophénol	µg/l	-		-	<10	-	<10	-				-	<10	-				
4-nitrophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
Phénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2-chlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
3-chlorophénol	µg/l	-		-	<1		<1						<1	-				
4-chlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,3-dichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,4 + 2,5-dichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,6-dichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
3,4-dichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
3,5-dichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
Pentachlorophénol	µg/l	60		-	<1	-	<1	-				-	<1	-				
2,3,4,6-tétrachlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,3,5,6-tétrachlorophénol	µg/l	-		-	<1	-	<1	-				-	<1					
2,4,5-trichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,4,6-trichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,3,5-Trichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,3,4-Trichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,3,6-Trichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
2,3,4,5-Tétrachlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
3,4,5-Trichlorophénol	µg/l	-		-	<1	-	<1	-				-	<1	-				
ortho-Crésol	µg/l	-		-	<1	-	<1	-				-	<1	-				
para-Crésol	µg/l	-		-	<1	-	<1	-				-	<1	-				
Couleur observée	-	-		-		-		-		-		-		-		-		
Matières présentes	-	-		-		-		-		-		-		-		-		
Odeur	-	-		-		-		-		-		-		-		-		
Pluviométrie	mm	-		-		-		-		-		-		-		-		
Température	°C	45		-		-		-		-		-		-		-		

- signifie: pas de critère défini pour ce paramètre ou non analysé.

[1] Règlement numéro 2008-47 sur l'assainissement des eaux de la CMM - Annexe 1, Colonne C : Valeurs applicables aux déversements dans les réseaux d'égout pluviaux ou dans les cours d'eau.

[2] Les résultats sont exprimés en équivalence toxique totale, échelle de l'OMS.

[3] Critères de la qualité de l'eau de surface au Québec, critère de protection de la faune terrestre piscivore.

[4] Somme des concentrations des HAP suivants : Benzo(a)anthracène, Benzo (b) fluoranthène, Benzo (j) fluoranthène, Benzo (k) fluoranthène, Benzo (a) pyrène, Chrysène, Dibenzo (a,h) anthracène, Dibenzo (a,i) pyrène et Indéno (1,2,3-cd) pyrène.

[5] Somme des concentrations des HAP suivants : Acénaphtène, Anthracène, Benzo (g,h,i) pérylène, Benzo (e) pyrène, Fluoranthène, Fluorène, Naphtalène, Phénanthrène et Pyrène.

[6] 12 mg/L si pH ≤7,56 mg/L si 7,5<pH≤8,02 mg/L si 8,0<pH≤8,50,7 mg/L si 8,5<pH

[7] Dû à l'interférence de la matrice, la limite de détection a été augmentée.

(*) Le résultat est celui de l'échantillon prélevé en duplicata

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Tableau 1 : Résultats analytiques des échantillons d'eau prélevés entre le 2 juin et le 7 juin 2017 en fonction des critères du Règlement numéro 2008-47 de la CMM

Hydro Québec

Paramètres	**Unités**	**Norme de la CMM[1]**	**Échantillons**													
			EB-2-2017-06-02-LAV	EB-2R-2017-06-02-LAV	EB-PCP-2017-06-07-LAV	EB-PCPR-2017-06-07-LAV	EB-ACC-2017-06-07-LAV	ET-12-2017-06-05-LAV	ET-12R-2017-06-05-LAV	ET-13-2017-06-07-LAV	ET-13R-2017-06-07-LAV	EAU PRECIPITATION-LAV	PE-1-2017-06-07-LAV	PE-2-2017-06-07-LAV	OA-2017-06-07-LAV	OAR-2017-06-07-LAV
Séquence			Amont des systèmes de traitement	Duplicata	Eau brute	Duplicata	Eau brute	Amont des Saules	Duplicata	Aval des unités de traitements	Duplicata	Eau de précipitation	Puisard du BEP	Puisard du BEP	Amont des systèmes de traitement	Duplicata
Date d'échantillonnage			02-juin-17	02-juin-17	06-juin-17	06-juin-17	06-juin-17	05-juin-17	05-juin-17	07-juin-17	07-juin-17	07-juin-17	07-juin-17	07-juin-17	07-juin-17	07-juin-17
Dioxines et furannes [2, 3]	pg/l	0,0031	80	-	6800	6300	-	1,3	-	0,0073	-	-	-	-	-	-
Métaux																
Aluminium	µg/l	3 000	31	32	240	-	110	42	-	<10	-	-	-	-	-	-
Argent	µg/l	120	<1,0	<1,0	<1.0	-	<1,0	<1,0	-	<1,0	-	-	-	-	-	-
Arsenic	µg/l	1 000	710	710	68	-	2600	180	-	3,4	-	-	-	-	-	-
Baryum	µg/l	1 000	15	15	7.1	-	<2,0	54	-	70	-	-	-	-	-	-
Cadmium	µg/l	100	0,23	0,29	<0.20	-	1	<0,20	-	<0,20	-	-	-	-	-	-
Chrome	µg/l	1 000	92	96	15	-	330	8,5	-	<5,0	-	-	-	-	-	-
Chrome hexavalent	µg/l	40	<8	<8	<40	-	<8	<8	-	<8	-	-	-	-	-	-
Cobalt	µg/l	-	<1,0	<1,0	<1.0	-	1,5	2,7	-	1,8	-	-	-	-	-	-
Cuivre	µg/l	1 000	350	360	37	-	2000	34	-	5,5	-	-	-	-	-	-
Étain	µg/l	1 000	<2,0	<2,0	<2.0	-	<2,0	<2,0	-	<2,0	-	-	-	-	-	-
Fer	µg/l	15 000	920	940	220	-	80	2700	-	450	-	-	-	-	-	-
Manganèse	µg/l	100	200	200	65	-	130	400	-	250	-	4,2	190	190	93	93
Molybdène	µg/l	-	1,4	1,4	1.1	-	4,0	17	-	13	-	-	-	-	-	-
Mercure	µg/l	1	<0,10	<0,10	<0.10	-	0,11	<0,10	-	<0,10	-	-	-	-	-	-
Nickel	µg/l	1 000	<2,0	<2,0	9.2	-	20	18	-	3,3	-	-	-	-	-	-
Plomb	µg/l	100	1	1	1.8	-	<0,50	0,68	-	<0,50	-	-	-	-	-	-
Sélénium	µg/l	20	4,1	4,2	<3.0	-	27	<3,0	-	<3,0	-	-	-	-	-	-
Zinc	µg/l	1 000	120	130	350	-	11	13	-	7,3	-	-	-	-	-	-
Inorganiques																
DCO	mg/l- O2	60	-	-	-	-	-	-	-	18	17	-	-	-	-	-
pH	pH	6 à 9,5	6,9	-	6,63	-	6,22	7,6	-	7,41	-	-	-	-	-	-
Nitrate et Nitrite	mg/l	-	-	-	-	-	-	0,045	0,05	<0,02	-	-	-	-	-	-
Composés phénoliques																
2,4-diméthylphénol	µg/l	-	<1,0	-	<0,60	<0,60	-	<0,60	-	<0,60	-	-	-	-	-	-
2,4-Dinitrophénol	µg/l	-	<10	-	<19 (7)	<19 (7)	-	<10	-	<10	-	-	-	-	-	-
2-Méthyl-4,6-dinitrophénol	µg/l	-	<10	-	<10	<10	-	<10	-	<10	-	-	-	-	-	-
4-nitrophénol	µg/l	-	<1,0	-	<1,0	<1,0	-	<1,0	-	<1,0	-	-	-	-	-	-
Phénol	µg/l	-	2,3	-	0,71	0,7	-	0,77	-	<0,60	-	-	-	-	-	-
2-chlorophénol	µg/l	-	<1,0	-	<0,50	<0,50	-	<0,50	-	<0,50	-	-	-	-	-	-
3-chlorophénol	µg/l	-	1,7	-	<0,50	<0,50	-	<0,50	-	<0,50	-	-	-	-	-	-
4-chlorophénol	µg/l	-	<1,0	-	<0,40	<0,40	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3-dichlorophénol	µg/l	-	<1,0	-	<0,50	<0,50	-	<0,50	-	<0,50	-	-	-	-	-	-
2,4 + 2,5-dichlorophénol	µg/l	-	<1,0	-	<0,30	<0,30	-	<0,30	-	<0,30	-	-	-	-	-	-
2,6-dichlorophénol	µg/l	-	<1,0	-	<0,40	<0,40	-	<0,40	-	<0,40	-	-	-	-	-	-
3,4-dichlorophénol	µg/l	-	<1,0	-	<0,88 (7)	<0,85 (7)	-	<0,40	-	<0,40	-	-	-	-	-	-
3,5-dichlorophénol	µg/l	-	1,1	-	<0,40	<0,40	-	<0,40	-	<0,40	-	-	-	-	-	-
Pentachlorophénol	µg/l	60	9,2	-	1400	1600	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,4,6-tétrachlorophénol	µg/l	-	1,2	-	77	73	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,5,6-tétrachlorophénol	µg/l	-	<1,0	-	16	15	-	0,41	-	<0,40	-	-	-	-	-	-
2,4,5-trichlorophénol	µg/l	-	<1,0	-	<0,40	<0,40	-	<0,40	-	<0,40	-	-	-	-	-	-
2,4,6-trichlorophénol	µg/l	-	<1,0	-	0,71	0,69	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,5-Trichlorophénol	µg/l	-	<1,0	-	<0,40	<0,40	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,4-Trichlorophénol	µg/l	-	<1,0	-	<0,40	<0,40	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,6-Trichlorophénol	µg/l	-	<1,0	-	<0,40	<0,40	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,4,5-Tétrachlorophénol	µg/l	-	<1,0	-	4,3	4,1	-	<0,40	-	<0,40	-	-	-	-	-	-
3,4,5-Trichlorophénol	µg/l	-	2,4	-	0,75	0,72	-	<0,40	-	<0,40	-	-	-	-	-	-
2-Nitrophénol	µg/l	-	<1,0	-	-	-	-	-	-	-	-	-	-	-	-	-
o-Crésol	µg/l	-	<1,0	-	<1,0	<1,0	-	<1,0	-	<1,0	-	-	-	-	-	-
m-Crésol	µg/l	-	<1,0	-	-	-	-	-	-	-	-	-	-	-	-	-
p-Crésol	µg/l	-	5,3	-	<1,2 (7)	<1,2 (7)	-	1,8	-	<1,0	-	-	-	-	-	-
Couleur observée	-	-														
Matières présentes	-	-														
Odeur	-	-														
Pluviométrie	mm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Température	°C	45														

- signifie: pas de critère défini pour ce paramètre ou non analysé.

(1) Règlement numéro 2008-47 sur l'assainissement des eaux de la CMM - Annexe 1, Colonne C : Valeurs applicables aux déversements dans les réseaux d'égout pluviaux ou dans les cours d'eau.
(2) Les résultats sont exprimés en équivalence toxique totale, échelle de l'OMS.
(3) Critères de la qualité de l'eau de surface au Québec, critère de protection de la faune terrestre piscivore.
(4) Somme des concentrations des HAP suivants : Benzo(a)anthracène, Benzo (b) fluoranthène, Benzo (j) fluoranthène, Benzo (k) fluoranthène, Benzo (a) pyrène, Chrysène, Dibenzo (a,h) anthracène, Dibenzo (a,i) pyrène et Indéno (1,2,3-cd) pyrène.
(5) Somme des concentrations des HAP suivants : Acénaphtène, Anthracène, Benzo (g,h,i) pérylène, Benzo (e) pyrène, Fluoranthène, Fluorène, Naphtalène, Phénanthrène et Pyrène.
(6) 12 mg/L si pH ≤7,56 mg/L si 7,5<pH≤8,02 mg/L si 8,0<pH≤8,50,7 mg/L si 8,5<pH
(7) Dû à l'interférence de la matrice, la limite de détection a été augmentée.

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Tableau 2 : Résultats analytiques des échantillons d'eau prélevés entre le 4 août et le 9 août 2017 en fonction des critères du Règlement numéro 2008-47 de la CMM

Hydro Québec

Paramètres	**Unités**	**Norme de la CMM**[1]	**Échantillons**													
			EB-2-2017-08-04-LAV	EB-2R-2017-08-04-LAV	EB-PCP-2017-08-04-LAV	EB-ACC-2017-08-04-LAV	EB-ACCR-2017-08-04-LAV	ET-12-2017-08-07-LAV	ET-12R-2017-08-07-LAV	ET-13-2017-08-09-LAV	ET-13R-2017-08-09-LAV	EAU PRECIPITATION-LAV	PE-1-2017-08-04-LAV	PE-2-2017-08-04-LAV	PE-2R-2017-08-04-LAV	OA-2017-08-04-LAV
Séquence			Amont des systèmes de traitement	Duplicata	Eau brute	Eau brute	Duplicata	Amont des Saules	Duplicata	Aval des unités de traitements	Duplicata	Eau de précipitation	Puisard du BEP	Puisard du BEP	Duplicata	Amont des systèmes de traitement
Date d'échantillonnage			04-août-17	04-août-17	04-août-17	04-août-17	04-août-17	07-août-17	07-août-17	09-août-17	09-août-17	04-août-17	04-août-17	04-août-17	04-août-17	04-août-17
Dioxines et furannes [2, 3]	pg/l	0,0031	110	-	3700	-	-	2,1	-	0,023	-	-	-	-	-	-
Métaux																
Aluminium	µg/l	3 000	48	-	420	130	86	82	-	22	-	-	-	-	-	-
Argent	µg/l	120	<1,0	-	<1,0	<1,0	<1,0	<1,0	-	<1,0	-	-	-	-	-	-
Arsenic	µg/l	1 000	990	-	54	11000	10000	230	-	32	-	-	-	-	-	-
Baryum	µg/l	1 000	16	-	89	9,4	9,9	72	-	75	-	-	-	-	-	-
Cadmium	µg/l	100	<0,20	-	0,59	2	2	<0,20	-	<0,20	-	-	-	-	-	-
Chrome	µg/l	1 000	53	-	31	1300	1300	19	-	<5,0	-	-	-	-	-	-
Chrome hexavalent	µg/l	40	<8	-	<80 (7)	<16	<16	<8	-	18	-	-	-	-	-	-
Cobalt	µg/l	-	<1,0	-	8	4,2	4,1	1,8	-	2,9	-	-	-	-	-	-
Cuivre	µg/l	1 000	250	-	91	4400	4100	22	-	<1,0	-	-	-	-	-	-
Étain	µg/l	1 000	<2,0	-	<2,0	3,4	2,7	<2,0	-	<2,0	-	-	-	-	-	-
Fer	µg/l	15 000	550	-	970	270	250	11000	-	3000	-	-	-	-	-	-
Manganèse	µg/l	100	120	-	1300	390	380	710	-	620	-	22	150	130	110	130
Molybdène	µg/l	-	3,4	-	3,1	21	22	8,3	-	21	-	-	-	-	-	-
Mercure	µg/l	1	<0,10	-	<0,10	0,42	0,44	<0,10	-	<0,10	-	-	-	-	-	-
Nickel	µg/l	1 000	<2,0	-	33	58	57	15	-	4,6	-	-	-	-	-	-
Plomb	µg/l	100	0,64	-	7,9	1,7	1,4	<0,50	-	<0,50	-	-	-	-	-	-
Sélénium	µg/l	20	5,3	-	3,5	150	140	<3,0	-	<3,0	-	-	-	-	-	-
Zinc	µg/l	1 000	90	-	1600	92	87	16	-	7,1	-	-	-	-	-	-
Inorganiques																
DCO	mg/l- O2	60	-	-	-	-	-	-	-	51	-	-	-	-	-	-
pH	pH	6 à 9,5	7,47	-	7,21	7,11	-	7,81	7,84	7,58	-	-	-	-	-	-
Nitrate et Nitrite	mg/l	-	-	-	-	-	-	<0,2	-	<2,0	<2,0	-	-	-	-	-
Composés phénoliques																
2,4-diméthylphénol	µg/l	-	<0,60	<0,60	<0,60	-	-	<0,60	-	<0,60	-	-	-	-	-	-
2,4-Dinitrophénol	µg/l	-	<10	<10	<21 (7)	-	-	<10	-	<10	-	-	-	-	-	-
2-Méthyl-4,6-dinitrophénol	µg/l	-	<10	<10	<10	-	-	<10	-	<10	-	-	-	-	-	-
4-nitrophénol	µg/l	-	<1,0	<1,0	<1,1 (7)	-	-	<1,0	-	<1,0	-	-	-	-	-	-
Phénol	µg/l	-	2,3	1,8	0,6	-	-	<0,60	-	6,8	-	-	-	-	-	-
2-chlorophénol	µg/l	-	<0,50	<0,50	<0,50	-	-	<0,50	-	<0,50	-	-	-	-	-	-
3-chlorophénol	µg/l	-	<0,50	<0,50	<0,50	-	-	<0,50	-	<0,50	-	-	-	-	-	-
4-chlorophénol	µg/l	-	<0,40	<0,40	<0,40	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3-dichlorophénol	µg/l	-	<0,50	<0,50	<0,50	-	-	<0,50	-	<0,50	-	-	-	-	-	-
2,4 + 2,5-dichlorophénol	µg/l	-	<0,30	<0,30	<0,30	-	-	<0,30	-	<0,30	-	-	-	-	-	-
2,6-dichlorophénol	µg/l	-	<0,40	<0,40	<0,40	-	-	<0,40	-	<0,40	-	-	-	-	-	-
3,4-dichlorophénol	µg/l	-	<0,40	<0,40	<0,40	-	-	<0,40	-	<0,40	-	-	-	-	-	-
3,5-dichlorophénol	µg/l	-	0,42	0,42	<0,40	-	-	<0,40	-	<0,40	-	-	-	-	-	-
Pentachlorophénol	µg/l	60	4	4	2600	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,4,6-tétrachlorophénol	µg/l	-	0,53	0,5	110	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,5,6-tétrachlorophénol	µg/l	-	1,2	1,3	36	-	-	0,82	-	0,53	-	-	-	-	-	-
2,4,5-trichlorophénol	µg/l	-	<0,40	<0,40	0,62	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2,4,6-trichlorophénol	µg/l	-	<0,40	<0,40	1,7	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,5-Trichlorophénol	µg/l	-	<0,40	<0,40	0,93	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,4-Trichlorophénol	µg/l	-	<0,40	<0,40	<0,40	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,6-Trichlorophénol	µg/l	-	<0,40	<0,40	<0,40	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2,3,4,5-Tétrachlorophénol	µg/l	-	<0,40	<0,40	11	-	-	<0,40	-	<0,40	-	-	-	-	-	-
3,4,5-Trichlorophénol	µg/l	-	<0,40	<0,40	<0,40	-	-	<0,40	-	<0,40	-	-	-	-	-	-
2-Nitrophénol	µg/l	-	-	-	-	-	-	-	-		-	-	-	-	-	-
o-Crésol	µg/l	-	<1,0	<1,0	<1,0	-	-	<1,0	-	<1,0	-	-	-	-	-	-
m-Crésol	µg/l	-	-	-	-	-	-	-	-		-	-	-	-	-	-
p-Crésol	µg/l	-	2,3	2,2	<1,0	-	-	<1,0	-	<1,0	-	-	-	-	-	-
Couleur observée	-	-														
Matières présentes	-	-														
Odeur	-	-														
Pluviométrie	mm	-	-	-	-		-	-	-	-	-	-	-	-	-	-
Température	°C	45														

- signifie: pas de critère défini pour ce paramètre ou non analysé.

(1) Règlement numéro 2008-47 sur l'assainissement des eaux de la CMM - Annexe 1, Colonne C : Valeurs applicables aux déversements dans les réseaux d'égout pluviaux ou dans les cours d'eau.
(2) Les résultats sont exprimés en équivalence toxique totale, échelle de l'OMS.
(3) Critères de la qualité de l'eau de surface au Québec, critère de protection de la faune terrestre piscivore.
(4) Somme des concentrations des HAP suivants : Benzo(a)anthracène, Benzo (b) fluoranthène, Benzo (j) fluoranthène, Benzo (k) fluoranthène, Benzo (a) pyrène, Chrysène, Dibenzo (a,h) anthracène, Dibenzo (a,i) pyrène et Indéno (1,2,3-cd) pyrène.
(5) Somme des concentrations des HAP suivants : Acénaphtène, Anthracène, Benzo (g,h,i) pérylène, Benzo (e) pyrène, Fluoranthène, Fluorène, Naphtalène, Phénanthrène et Pyrène.
(6) 12 mg/L si pH ≤7,56 mg/L si 7,5<pH≤8,02 mg/L si 8,0<pH≤8,50,7 mg/L si 8,5<pH
(7) Dû à l'interférence de la matrice, la limite de détection a été augmentée.

Tableau 3 : Résultats analytiques des échantillons d'eau prélevés entre le 3 et le 8 novembre 2017 en fonction des critères du Règlement numéro 2008-47 de la CMM

Paramètres	Unités	Norme de la CMM[1]	Échantillons												
			EB-2-2017-11-03-LAV	EB-2R-2017-11-03-LAV	EB-ACC-2017-11-03-LAV	ET-12-2017-11-06-LAV	ET-12R-2017-11-06-LAV	ET-13-2017-11-08-LAV	ET-13R-2017-11-08-LAV	EAU-PRECIPITATION-LAV	PE1-2017-11-03-LAV	PR1-2017-11-03-LAV	PE2-2017-11-03-LAV	PR2-2017-11-03-LAV	OA-2017-11-03-LAV
Séquence			Amont des systèmes de traitement	Duplicata	Eau brute	Amont des Saules	Duplicata	Aval des unités de traitements	Duplicata	Eau de précipitation	Puisard du BEP	Duplicata	Puisard du BEP	Duplicata	Amont des systèmes de traitement
Date d'échantillonnage			03-nov-17	03-nov-17	03-nov-17	06-nov-17	06-nov-17	08-nov-17	08-nov-17	03-nov-17	03-nov-17	03-nov-17	03-nov-17	03-nov-17	03-nov-17
Dioxines et furannes [2, 3]	pg/l	0,0031	120	-	-	1,3	-	0,57	-	-	-	-	-	-	-
Métaux															
Aluminium	µg/l	3 000	36	42	18	20	-	15	-	-	-	-	-	-	-
Argent	µg/l	120	<1,0	<1,0	<1,0	<1,0	-	<1,0	-	-	-	-	-	-	-
Arsenic	µg/l	1 000	520	520	1100	69	-	37	-	-	-	-	-	-	-
Baryum	µg/l	1 000	7,8	7,9	2,4	37	-	45	-	-	-	-	-	-	-
Cadmium	µg/l	100	<0,20	<0,20	<0,20	<0,20	-	<0,20	-	-	-	-	-	-	-
Chrome	µg/l	1 000	52	50	110	7,3	-	<5,0	-	-	-	-	-	-	-
Chrome hexavalent	µg/l	40	<8	<8	<8	<8	-	<8	-	-	-	-	-	-	-
Cobalt	µg/l	-	<1,0	<1,0	<1,0	<1,0	-	2,3	-	-	-	-	-	-	-
Cuivre	µg/l	1 000	180	170	290	11	-	<1,0	-	-	-	-	-	-	-
Étain	µg/l	1 000	<2,0	<2,0	<2,0	<2,0	-	<2,0	-	-	-	-	-	-	-
Fer	µg/l	15 000	370	410	<60	2200	-	3200	-	-	-	-	-	-	-
Manganèse	µg/l	100	49	49	53	270	-	490	-	2,4	150	150	62	61	51
Molybdène	µg/l	-	1,8	1,8	2,3	7,7	-	5,8	-	-	-	-	-	-	-
Mercure	µg/l	1	0,17	<0,10	<0,10	<0,10	-	<0,10	-	-	-	-	-	-	-
Nickel	µg/l	1 000	<2,0	<2,0	2,4	5	-	3,9	-	-	-	-	-	-	-
Plomb	µg/l	100	0,66	0,65	<0,50	<0,50	-	<0,50	-	-	-	-	-	-	-
Sélénium	µg/l	20	5,3	5,1	14	<3,0	-	<3,0	-	-	-	-	-	-	-
Zinc	µg/l	1 000	170	180	24	<7,0	-	<7,0	-	-	-	-	-	-	-
Inorganiques															
DCO	mg/l- O2	60	-	-	-	-	-	32	35	-	-	-	-	-	-
pH	pH	6 à 9,5	7,17	-	6,93	7,79	-	7,5	-	-	-	-	-	-	-
Nitrate et Nitrite	mg/l	-	-	-	-	0,5	0,52	<0,2	-	-	-	-	-	-	-
Composés phénoliques															
2,4-diméthylphénol	µg/l	-	<1,0	-	-	<0,60	-	<0,60	-	-	-	-	-	-	-
2,4-Dinitrophénol	µg/l	-	<10	-	-	<10	-	<10	-	-	-	-	-	-	-
2-Méthyl-4,6-dinitrophénol	µg/l	-	<10	-	-	<10	-	<10	-	-	-	-	-	-	-
4-nitrophénol	µg/l	-	<1,0	-	-	<1,0	-	<1,0	-	-	-	-	-	-	-
Phénol	µg/l	-	1,2	-	-	<0,60	-	<0,60	-	-	-	-	-	-	-
2-chlorophénol	µg/l	-	<1,0	-	-	<0,50	-	<0,50	-	-	-	-	-	-	-
3-chlorophénol	µg/l	-	<1,0	-	-	<0,50	-	<0,50	-	-	-	-	-	-	-
4-chlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2,3-dichlorophénol	µg/l	-	<1,0	-	-	<0,50	-	<0,50	-	-	-	-	-	-	-
2,4 + 2,5-dichlorophénol	µg/l	-	<1,0	-	-	<0,30	-	<0,30	-	-	-	-	-	-	-
2,6-dichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
3,4-dichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
3,5-dichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
Pentachlorophénol	µg/l	60	7,6	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2,3,4,6-tétrachlorophénol	µg/l	-	1	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2,3,5,6-tétrachlorophénol	µg/l	-	<1,0	-	-	0,41	-	<0,40	-	-	-	-	-	-	-
2,4,5-trichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2,4,6-trichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2,3,5-Trichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2,3,4-Trichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2,3,6-Trichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2,3,4,5-Tétrachlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
3,4,5-Trichlorophénol	µg/l	-	<1,0	-	-	<0,40	-	<0,40	-	-	-	-	-	-	-
2-Nitrophénol	µg/l	-	<1,0	-	-	-	-	-	-	-	-	-	-	-	-
o-Crésol	µg/l	-	<1,0	-	-	<1,0	-	<1,0	-	-	-	-	-	-	-
m-Crésol	µg/l	-	<1,0	-	-	-	-	-	-	-	-	-	-	-	-
p-Crésol	µg/l	-	<1,0	-	-	<1,0	-	<1,0	-	-	-	-	-	-	-
Couleur observée	-	-													
Matières présentes	-	-													
Odeur	-	-													
Pluviométrie	mm	-	-	-		-	-	-	-	-	-		-	-	-
Température	°C	45													

- signifie: pas de critère défini pour ce paramètre ou non analysé.

(1) Règlement numéro 2008-47 sur l'assainissement des eaux de la CMM - Annexe 1, Colonne C : Valeurs applicables aux déversements dans les réseaux d'égout pluviaux ou dans les cours d'eau.
(2) Les résultats sont exprimés en équivalence toxique totale, échelle de l'OMS.
(3) Critères de la qualité de l'eau de surface au Québec, critère de protection de la faune terrestre piscivore.
(4) Somme des concentrations des HAP suivants : Benzo(a)anthracène, Benzo (b) fluoranthène, Benzo (j) fluoranthène, Benzo (k) fluoranthène, Benzo (a) pyrène, Chrysène, Dibenzo (a,h) anthracène, Dibenzo (a,i) pyrène et Indéno (1,2,3-cd) pyrène.
(5) Somme des concentrations des HAP suivants : Acénaphtène, Anthracène, Benzo (g,h,i) pérylène, Benzo (e) pyrène, Fluoranthène, Fluorène, Naphtalène, Phénanthrène et Pyrène.
(6) 12 mg/L si pH ≤7,56 mg/L si 7,5<pH≤8,02 mg/L si 8,0<pH≤8,50,7 mg/L si 8,5<pH
(7) Dû à l'interférence de la matrice, la limite de détection a été augmentée.

Tableau 4 : Résultats analytiques des échantillons de médias filtrants et de végétaux prélevés le 29 septembre 2016 et le 3 novembre 2017

Paramètres	Unités	Échantillons																															
		SUAFH-1	SUAH-1	SUAFB-1	SUAB-1	SUAFH-2	SUAH-2	SUAFB-2	SUAB-2	SUEFH-3	SUEFB-3	SUEFH-4	SUEFB-4	SUEH-1	SUEH-2	SUEB-1	SUEB-2	RAAF-1	RAAF	RAEF-1	RAEF	TIAF-1	TIAF	TIEF-1	TIEF	FEAF-1	FEAF	FEEF-1	FEEF	FETM-1	FETM-1	FETM-2	FETM-2
Séquence		Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Médias filtrants	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux	Végétaux
Année d'échantillonnage		2016	2017	2016	2017	2016	2017	2016	2017	2016	2016	2016	2016	2017	2017	2017	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Dioxines et furannes	pg/g	2,4	0,49	0,33	0,49	0,25	0,5	0,35	0,59	0,27	0,42	0,31	0,22	0,53	0,5	0,56	0,43	0,14	0,32	0,3	0,07	0,0018	0,0059	0,002	0,0087	0,13	0,016	0,18	0,24	0,14	0,096	0,19	0,06
Métaux																																	
Argent (Ag)	mg/kg	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,5	<0,5	<0,5	<0,50	<0,50	<0,50	<0,50	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10
Arsenic (As)	mg/kg	<5	<5,0	<5	<5,0	<5	<5,0	<5	<5,0	<5	<5	<5	<5	<5,0	<5,0	<5,0	<5,0	<0,5	6,5	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50
Baryum (Ba)	mg/kg	21	28	32	28	22	27	25	18	20	22	21	24	23	27	36	24	9	12	8	8,4	7	8,8	10	11	19	27	18	22	11	9,7	15	28
Cadmium (Cd)	mg/kg	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,5	<0,5	<0,5	<0,50	<0,50	<0,50	<0,50	<0,2	<0,20	<0,2	<0,20	<0,2	<0,20	0,4	0,71	<0,2	0,73	0,5	1,1	2,1	2,9	0,9	4,4
Chrome (Cr)	mg/kg	10	12	12	20	8	12	9	12	8	10	11	10	12	14	12	13	<0,5	3,1	<0,5	1,4	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50	<0,5	<0,50
Cobalt (Co)	mg/kg	4	8,6	4	9,7	4	14	4	21	3	4	11	4	15	18	5,3	15	<1	5,3	<1	3,3	<1	<1,0	<1	<1,0	<1	<1,0	1	<1,0	2	3,1	1	1,5
Cuivre (Cu)	mg/kg	11	31	8	28	12	56	10	96	10	12	47	12	65	89	15	64	7	80	4	47	4	6,5	5	4	2	3,6	3	4,4	5	5,2	5	3,8
Etain (Sn)	mg/kg	<4	<4,0	<4	<4,0	<4	<4,0	<4	<4,0	<4	<4	<4	<4	<4,0	<4,0	<4,0	<4,0	<2	2,6	<2	2,8	<2	<2,0	<2	<2,0	<2	<2,0	<2	<2,0	<2	<2,0	<2	<2,0
Manganèse (Mn)	mg/kg	110	130	82	110	87	160	110	140	100	120	160	110	190	180	120	160	13	84	4	43	15	16	11	29	57	55	57	62	440	890	320	680
Molybdène (Mo)	mg/kg	6	47	<1	52	16	130	4	240	2	7	100	6	130	180	14	140	2	44	<1	31	<1	<1,0	<1	<1,0	7	6,6	4	4,6	<1	<1,0	<1	<1,0
Nickel (Ni)	mg/kg	34	110	19	140	51	420	23	620	21	30	270	35	400	560	59	340	16	200	7	120	1,1	1,6	<0,5	0,57	6,4	6,7	8,8	8,8	3	3,4	2,9	1,8
Plomb (Pb)	mg/kg	<5	<5,0	<5	<5,0	<5	<5,0	<5	<5,0	<5	<5	<5	<5	<5,0	<5,0	<5,0	<5,0	<0,3	1,1	<0,3	0,4	<0,3	<0,30	<0,3	<0,30	0,7	0,57	0,6	0,58	0,6	0,81	0,5	0,69
Zinc (Zn)	mg/kg	15	13	14	25	13	17	17	13	12	19	15	15	16	19	19	21	23	51	20	54	39	64	52	87	21	96	40	91	200	190	160	630
Composés phénoliques																																	
o-Crésol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	0,1	<0,1	<0,50	<0,1	<0,50	0,4	1,3	0,5	0,62
m-Crésol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
p-Crésol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,2 (1)	<0,10	<0,2 (1)	<0,10	<0,1	<0,13 (1)	<0,1	<0,42 (1)	<0,3 (1)	<0,69 (1)	<0,3 (1)	<0,66 (1)	<7 (1)	<15 (1)	<20 (1)	<12 (1)
2,4-Diméthylphénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,5 (1)	<0,50	<0,5 (1)	<0,50
2-Nitrophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
4-Nitrophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,18 (1)	<0,1	<0,50 (1)	<0,1	<0,50	<0,2 (1)	<0,50	<0,1	<0,50	<0,1	<0,50
Phénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	0,2	<0,10	<0,1	<0,10	<0,1	0,24	0,4	0,54	0,4	0,64	4,5	12	4,2	12
2-Chlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
3-Chlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
4-Chlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,3-Dichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,4 + 2,5-Dichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,6-Dichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
3,4-Dichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
3,5-Dichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
Pentachlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,3,4,5-Tétrachlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,3,4,6-Tétrachlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,3,5,6-Tétrachlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,3,4-Trichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,3,5-Trichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,3,6-Trichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,4,5-Trichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
2,4,6-Trichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50	<0,1	<0,50
3,4,5-Trichlorophénol	mg/kg	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,1	<0,10	<0,2 (1)	<0,50	<0,2 (1)	<0,50	<0,1	<0,50	<0,1	<0,50

- signifie: pas de critère défini pour ce paramètre ou non analysé.

(1) Dû à l'interférence de la matrice, la limite de détection a été augmentée.

Annexe 5 | Données hydrologique récoltées en 2016, 2017 et 2018 pour le calcul de l'affluent des marais filtrants, la réalisation du bilan hydrique du marais de saules et l'estimation de l'évaporation de l'eau libre par bac d'évaporation

Données 2016

Date	Pompe système 1		Pompe système 2		Pompe marais		Pompe IRBV		Affluent saules		Effluent saules		Bac 1 (cm)
	Évèn.	Heures	Évèn.	Heures	Minutes	Débit (L/min)	Minutes	Débit (L/min)	Gallons	**Litres**	Gallons	**Litres**	
09-mai	84	1070,89	13084	883,61	172	40	1764	12	44330	0	47766	0	
16-mai						40	NA	12	49102	18065	48803	3926	
18-mai						40	NA	12	50335	22733	49619	7015	
18-mai						40	NA	12	50519	23429	49737	7459	
20-mai	8	1071,56	13247	883,61	174	40	1784	12	51917	28721	50673	11003	
25-mai	8	1074,73	13306	883,61	294	40	3016	12	57047	48140	52317	17229	
26-mai	8	1075,36	13318	883,61	318	40	3266	12	57818	51058	52723	18764	
27-mai	8	1075,93	13329	883,61	343	40	3527	12	58616	54082	53105	20210	15,00
30-mai	8	1077,86	13366	883,61	416	40	4268	12	61396	64604	54998	27375	15,50
03-juin	8	1080,25	13414	883,61	513	40	5269	12	64057	74678	57123	35422	15,50
07-juin	8	1082,94	13462	883,61	611	40	6271	12	70037	97312	60825	49435	18,00
09-juin	8	1084,3	13486	883,61	661	40	6773	12	72503	106647	62104	54277	18,00
13-juin	8	1086,81	13534	883,61	757	40	7773	12	76181	120571	64451	63158	17,50
17-juin	8	1089,56	13582	883,61	855	40	8775	12	79566	133384	66399	70534	16,00

21-juin	9	1091,49	13616	883,61	18	40	188	8	81217	139633	67118	73257	14,50
23-juin	9	1092,44	13632	883,61	69	40	709	8	82507	144518	67699	75454	14,00
27-juin	9	1094,2	13664	883,61	165	40	1690	8	85963	157599	68048	76776	12,00
29-juin	9	1095,06	13680	883,61	217	40	2217	8	89550	171179	69423	81981	23,50
04-juil	9	1097,97	13715	883,61	335	40	3432	8	91572	178834	71004	87966	17,50
08-juil	9	1097,47	13742	883,61	435	40	4465	8	92600	182724	71296	89069	15,00
12-juil	10	1100,02	13769	883,61	28	40	282	12	95698	194451	72536	93765	16,00
15-juil	10	1101,07	13788	883,61	101	40	1033	12	97023	199468	72903	95154	15,25
19-juil	10	1103,95	13838	883,61	NA	40		12	102600	220579	76160	107483	17,75
22-juil	10	1105,93	13872	883,61	271	40	2775	12	105426	231277	77535	112687	17,00
26-juil						40		12	109196	245544	79564	120368	17,00
27-juil	10	1109,29	13932	883,61	393	40	4027	12	110228	249452	80018	122087	16,25
29-juil	10	1110,68	13955	883,61	441	40	4517	12	112101	256545	80966	125676	15,50
02-août	10	1113,92	14006	883,61	543	40	5566	12	116372	272710	82821	132697	13,75
03-août						40		8	116826	274427	83169	134014	13,50
05-août	10	1115,41	14031	883,61	610	40	6260	8	118036	279011	83670	135910	13,00
09-août	10	1117,35	14064	883,61	713	40	7311	8	119521	284629	83903	136793	11,00
11-août	10	1118,25	14079	883,61	759	40	7774	3	120273	287477	84152	137735	10,00
16-août	10	1119,32	14106	883,61	97	40	1001	6	123020	297877	86144	145277	12,50
19-août	10	1121,73	14139	883,61	171	40	1752	6	129658	323005	90946	163453	19,50
23-août	10	1124,16	14183	883,61	268	40	2745	6	134275	340479	93302	172371	20,50
25-août	10	1125,19	14201	883,61	319	40	3276	6	135425	344835	93805	174275	19,75
30-août	10	1127,67	14245	883,61	440	40	4517	6	138638	356995	95021	178881	18,00
01-sept	10	1128,74	14263	883,61	485	40	4976	6	140684	364740	95847	182007	17,50
06-sept	10	1131,59	14311	883,61	612	40	6280	6	145054	381285	97231	187245	16,50
08-sept	10	1132,57	14328	883,61	657	40	6740	6	147073	388925	97933	189902	17,00
13-sept	10	1135,26	14375	883,61	780	40	8002	6	152623	409936	100363	199103	17,50

15-sept	10	1136,28	14391	883,61	828	40	8482	6	154235	416037	100724	200469	17,00
20-sept	10	1138,94	14433	883,61	954	40	9796	6	158847	433497	102452	207007	16,50
27-sept	10	1142,07	14484	883,61	1120	40	11497	6	163575	451393	104104	213261	14,75
29-sept	10	1142,38	14489	883,61		40		6	163908	452654	104210	213663	14,25
03-oct	10	1142,38	14489	883,61		40		6	163908	452654	104210	213663	13,00
06-oct	10	1142,38	14489	883,61		40		6	163908	452654	104210	213663	12,50
11-oct	10	1142,38	14489	883,61		40		6	163908	452654	104210	213663	14,00
17-oct	10	1145,47	14539	883,61	145	40	1492	6	168453	469857	105765	219548	15,00
24-oct	10	1148,62	14596	883,61	319	40	3276	6	181022	517439	112855	246389	
01-nov	10	1154,09	14693	883,61	517	40	5311	6	181022	517439	116892	261671	
04-nov	10	1154,82	14705	883,61	24	40	240	10	182377	522566	119013	269701	
10-nov	10	1158,7	14775	883,61		40		10	189331	548891	123283	285863	
16-nov	10	1161,06	14818	883,61	169	40	1732	10	192366	560380	125418	293943	
24-nov	12	1164	14871	883,61	366	40	3756	10	197567	580067	NA	NA	
30-nov	12	1165,55	14901	883,61	511	40	5248	10	201111	593481	131164	315697	
09-déc	12	1166,81	14925	883,61		40	NA	10	213399	639996	141216	353749	

Données 2017

Date	**Pompe système 1**		**Pompe système 2**		**Pompe marais**		**Pompe IRBV**		**Affluent saules**		**Effluent saules**		**Bac 1 (cm)**	**Bac 2 (cm)**
	Évèn.	Heures	Évèn.	Heures	Minutes	Débit (L/min)	Minutes	Débit (L/min)	Gallons	Litres	Gallons	Litres		
09-déc	12	1166,81	14925	883,61					213399	639996	141216	353749		
24-avr	12	1166,81	14925	883,61										
08-mai													12,50	12,25
11-mai													12,20	11,80

13-mai													11,70	11,70
15-mai	12	1166,81	14925	883,61					219494	830875	149199	564778	11,50	11,10
17-mai	12	1168,09	14997	883,61	48	6	488	40	220497	834673	149745	566845	11,10	10,60
19-mai	12	1169,08	15014	883,61	96	6	984	40	221224	837422	150247	568746	9,90	9,10
23-mai	12	1171,16	15052	883,61	193	6	1982	40	222989	844104	151633	573994	9,30	8,50
25-mai	12	1172,38	15072	883,61	244	6	2504	40	223521	846118	152279	576438	8,60	7,80
01-juin	12	1175,91	15129	883,61	413	6	4236	40	226204	856275	154401	584470	12,60	11,20
02-juin	12	1176,45	15138	883,61	437	6	4486	40	226695	858134	154619	585298	12,10	10,90
08-juin	12	1178,56	15178	883,61	559	6	5738	40	230379	872080	158002	598103	16,20	15,30
10-juin									231384	875884	158556	600199	15,70	14,20
12-juin	13	1180,48	15216	883,61	681	6	6990	40	232078	878512	158982	601810	15,20	13,40
15-juin	13	1181,68	15237	883,61	754	6	7742	40	232733	880988	159230	602750	13,90	11,90
18-juin									234300	886921	160513	607609	13,90	11,90
22-juin	13	1183,62	15271	883,61	926	6	9501	30	235100	889949	160812	608740	16,30	14,20
26-juin	13	1184,99	15296	883,61	1024	6	10506	30	236380	894795	161682	612031	16,40	14,70
28-juin	13	1185,71	15309	883,61	4	6	33	30	236837	896526	161885	612802	16,70	14,20
02-juil									238878	904251	163165	617647	17,70	14,90
04-juil	14	1188,19	15354	883,61	73	6	752	30	239428	906332	163465	618782	17,10	14,30
05-juil					97	6	1002	30	239737	907504	163565	619159	16,60	13,80
10-juil	14	1190,89	15403	883,61	219	6	2254	24	243296	920976	165844	627789	18,80	16,20
12-juil	14	1191,77	15418	883,61	268	6	2753	24	244189	924356	166452	630090	18,10	15,50
14-juil	14	1192,78	15435	883,61	317	6	3256	24	244911	927090	166843	631570	17,70	15,10
18-juil	14	1194,63	15474	883,61	414	6	4257	24	247523	936977	168842	639137	19,80	16,90
22-juil				102					247929	938511	168993	639707	19,60	16,90
26-juil	16	1196,51	15511	883,61	610	3	6258	20	249611	944881	169070	639998	20,20	17,40
28-juil	16	1197,32	15528	883,61	658	6	6761	20	250451	948061	169012	639778	16,40	13,40
01-août	16	1198,97	15560	883,61	756	6	7757	20	252778	956869	169059	639959	17,80	14,90

08-août	16	1201,67	15613	883,61	927	6	9516	20	256088	969397	171896	650698	18,70	15,80
11-août	17	1203,65	15651	883,61	51	6	522	40	257647	975301	172869	654381	17,70	14,70
14-août	17	1205,56	15687	883,61	124	6	1273	40	259948	984011	174507	660579	18,50	15,00
17-août	18	1207,5	15723	883,61	50	6	521	40	262190	992495	176072	666505	18,60	15,70
21-août	18	1209,93	15771	883,61	149	6	1529	40	265352	1004464	178220	674635	10,60	10,60
25-août	18	1212,39	15819	883,61	247	8	2535	40	268918	1017965	180889	684739	15,30	12,20
29-août	19	1215,15	15689	883,61	344	8	3535	40	272006	1029654	182744	691762	14,10	11,30
31-août	19	1216,68	15898	883,61	392	8	4027	40	273994	1037180	183936	696272	13,80	11,00
05-sept	19	1220,05	15961	883,61	514	8	5279	40	279058	1056348	187748	710702	16,60	13,80
08-sept	19	1221,81	15995	883,61	72	8	740	40	281505	1065613	189614	717766	17,10	14,40
10-sept									283384	1072725	190813	722304	16,90	14,10
12-sept	19	1224,01	16032	883,61	170	8	1742	40	285183	1079533	192027	726900	16,40	13,60
20-sept	19	1230,55	16143	883,61	365	8	3744	40	292263	1106334	196695	744570	14,20	12,20
22-sept	19	1231,93	16159	883,61	414	8	4246	40	293622	1111481	197240	746633	14,10	11,40
25-sept	20	1234,01	16195	883,61	51	8	521	40	296081	1120789	199041	753453	13,40	10,90
28-sept	20	1236,12	16231	883,61	125	8	1281	40	298524	1130037	200838	760255	13,30	11,10
30-sept									300109	1136037	202064	764895	12,90	10,40
03-oct	20	1239,14	16283	883,61	248	8	2538	40	302143	1143734	203436	770090	12,20	9,90
10-oct	20	1239,15	16284	883,61					303762	1149862	205065	776256	18,00	15,90
17-oct	21	1245,4	16399	883,61	171	8	1753	40	312240	1181956	212086	802831	19,50	17,30
20-oct	21	1247,29	16434	883,61	243	8	2494	40	314690	1191231	213982	810009	18,90	16,80
27-oct	21	1251,61	16518	883,61	415	8	4257	40	321304	1216266	219358	830361	21,50	194,00
30-oct	22	1253,52	16554	883,61	38	8	396	40	325685	1232852	223041	844301	25,50	23,70
09-nov	22	1259,19	16659	883,61	244	8	2504	40	336629	1274279	232254	879178	30,50	28,50

Données 2018

Date	**Pompe système 1**		**Pompe système 2**		**Pompe Marais**		**Pompe IRBV**		**P12 (entrée)**		**P13 (sortie)**	
	Évèn.	Heures	Évèn.	Heures	Minutes	Débit (L/min)	Minutes	Débit (L/min)	Gallons	Litres	Gallons	Litres
10-mai	27	1273,60	16895	883,61	0	0	0	0	368486	1394872	258720	979362
24-mai	27	1282,35	17062	883,61	341	10	3495	40	376182	1424003	261136	988505
31-mai	27	1287,30	17153	883,61	513	11	5259	40	379114	1435101	263568	997715
07-juin	27	1291,18	17234	883,61	682	7	7001	40	383971	1453486	267751	1013547
14-juin	27			883,61	853	7	8754	40	388301	1469878	271072	1026119
21-juin	27	1299,34	17403	883,61	171	7	1748	40	392877	1487199	274317	1038402
28-juin	27	1303,65	17487	883,61	341	7	3495	40	396267	1500034	276312	1045955
05-juil	27	1306,92	17551	883,61	167	6	1711	32	397796	1505823	276864	1048045
12-juil	27	1310,70	17626	883,61	75	10	762	32	399221	1511214	276957	1048398
19-juil	27			883,61	22	10	230	32	401594	1520197	277763	1051448
26-juil	27			883,61	21	10	219	32	404255	1530271	279277	1057179
02-août	32	1319,38	17799	883,61	70	10	720	32	406223	1537722	280378	1061347
09-août	32	1322,21	17855	883,61	241	10	2472	32	408656	1546932	281719	1066423
16-août	32	1324,99	17911	883,61	412	10	4226	32	410933	1555549	283032	1071393
23-août	32	1327,88	17967	883,61	21	10	219	32	413102	1563759	284373	1076467
30-août	32	1331,27	18031	883,61	193	10	1983	32	416376	1576156	286509	1084556
06-sept	33			883,61	21	10	219	32	419981	1589801	289600	1096256
13-sept	34	1336,63	18131	883,61	144	10	1471	32	422433	1599081	291559	1103671
20-sept	34	1339,34	18193	883,61	45	10	459	32	424600	1607286	292731	1108106
27-sept	34	1341,95	18247	883,61	215	10	2212	32	428749	1622989	296582	1122683
05-cot	34			883,61	410	10	4204	32	431919	1634992	299021	1131915
12-oct	34			883,61	167	10	1722	32	435618	1648993	302264	1144194
15-nov	34	1359,23	18586	883,61		10		32	452826	1714132	316286	1197272

Annexe 6 | Base de données météo pour la station du site d'entreposage de poteaux à Laval, de 2016 à 2018

Date	T.max (°C)	T.min (°C)	T.moy (°C)	Rad (MJ/m^2)	RH.moy (%)	RH.min (%)	RH.max (%)	Pluie (mm)	Vent (m/s)
2016-05-09	12,1	0,6	6,1	19,3	48,5	30	66	0	2,1
2016-05-10	20,4	4,8	12,5	28,7	37,6	22	51	0	1,7
2016-05-11	23,2	4,7	14,8	27,9	39	22	66	0	0,9
2016-05-12	26,7	8,1	18,1	25,4	38,1	26	59	0	0,8
2016-05-13	21,4	12,2	17,3	9,0	64,3	41	93	4,6	2
2016-05-14	21,5	10,6	15,2	20,5	64,1	45	82	6	1,9
2016-05-15	10,7	2,2	6,8	13,3	65,8	45	90	0,6	3,4
2016-05-16	9,3	1,9	5,4	9,6	57,7	46	89	0,8	3
2016-05-17	13,1	3,5	8,4	15,8	59,9	40	74	0	1,6
2016-05-18	19,6	2,9	11,5	25,7	56,5	36	79	0	0,8
2016-05-19	21,2	7,7	13,8	14,9	60,8	38	85	0	0,5
2016-05-20	24,9	6,5	17,1	28,2	55,8	30	90	0	1,6
2016-05-21	25,3	11,6	19	22,7	46,1	30	62	0	1,8
2016-05-22	27,2	11,3	19,4	28,0	50,8	30	72	0	1,3
2016-05-23	28,4	11	20,3	29,3	40,2	23	60	0	0,9
2016-05-24	30,2	10	21,4	27,9	42,4	16	76	0	0,8
2016-05-25	27,2	14	20,1	15,4	53,9	43	77	0	1,8
2016-05-26	25,4	10,2	18,7	26,4	45,5	21	87	0	1,3
2016-05-27	31,8	13,2	21,6	21,8	65,2	34	86	8	1,8
2016-05-28	28,6	17	22,7	24,4	63,6	42	98	0	1,5
2016-05-29	27,9	15,5	20	14,2	71,5	61	89	2,4	1,9
2016-05-30	30,2	20,1	24,8	26,1	65,5	45	92	2,2	3
2016-05-31	25,7	14,7	20,2	24,1	56,3	40	67	0	2
2016-06-01	25,9	12,7	19,2	28,6	54,7	41	71	0	1,8
2016-06-02	22	14,3	19,1	5,9	77,3	63	89	13,4	1,5
2016-06-03	26,8	15,7	21,4	28,7	61,5	37	92	0,2	1,8
2016-06-04	27,7	12,4	19,9	21,7	56,2	38	87	0	0,4
2016-06-05	19	14,3	17	2,9	82,3	57	95	34,4	1,9
2016-06-06	23,4	16,8	19,5	17,6	72,8	59	95	5,4	3,5
2016-06-07	22,7	14	17,8	17,4	70,1	51	92	3	2,3
2016-06-08	14	8,5	11,6	14,5	68,8	55	85	2	2,2
2016-06-09	13,9	8,1	10,4	8,4	65,4	51	85	0,4	2
2016-06-10	21,6	7,4	14,4	28,4	62,8	48	77	0,2	1,5
2016-06-11	16,9	10,9	14,7	7,2	74,7	67	90	0	1,1

2016-06-12	15,7	10,3	12,2	8,6	68,6	53	95	0,4	2,1
2016-06-13	20,9	10,1	15,7	24,7	66,6	34	83	0,2	1,4
2016-06-14	28,2	8,6	17,3	27,7	60	37	78	0	1,6
2016-06-15	30,2	11,4	20,4	28,3	57,2	29	84	0	0,8
2016-06-16	27,7	11,7	19,8	31,1	49,3	26	80	0	1,4
2016-06-17	28,8	15,4	25,2	35,3	46	28	78	0	0,8
2016-06-18	30,8	12,4	23	29,7	48,6	23	78	0	1,5
2016-06-19	33	19	25,4	27,7	48,1	38	64	0	2,8
2016-06-20	32,8	20,2	26,8	27,7	49,3	35	68	18,4	3,8
2016-06-21	23,8	15,7	20,3	27,8	45,3	29	78	0,4	2,1
2016-06-22	22	13,9	17,3	15,3	62,6	46	90	0,2	1,2
2016-06-23	24,9	12,7	18,7	28,1	51,9	32	79	0	1
2016-06-24	26,2	9,1	19,4	29,3	51,2	35	75	0	1,2
2016-06-25	30,4	13,8	24	29,4	51,3	28	78	0	1,4
2016-06-26	32,5	15,2	25,5	29,0	54,3	37	85	0	1,7
2016-06-27	27,8	20,2	25	10,7	69,7	53	91	4,2	2,5
2016-06-28	29,3	17,7	23	18,5	75,8	45	94	50,2	1,5
2016-06-29	23,2	14,4	18,8	12,4	82,3	61	95	1,6	1
2016-06-30	28,4	13,1	21,5	30,2	67,4	39	98	0,2	1,5
2016-07-01	28,2	14,2	21	19,6	64,3	40	90	5,6	1,3
2016-07-02	20,6	13,7	17,4	15,7	67,8	47	87	0,2	2,6
2016-07-03	26,7	12,7	19,5	25,5	60,4	33	92	0,2	1,7
2016-07-04	29,8	22	26,9	28,8	57,3	41	78	0,2	1,9
2016-07-05	31,1	15,4	24,7	28,6	52,5	35	72	0,2	1,6
2016-07-06	31,5	17,7	24,8	24,8	61	44	76	0	1,2
2016-07-07	25,9	16,4	20,4	17,0	78	65	88	0	1,7
2016-07-08	23,5	16,7	20	15,6	74,8	63	86	0	2,2
2016-07-09	19,6	16,2	18	2,8	88,8	79	96	1,8	2,1
2016-07-10	20,2	13,1	17	8,9	86,9	72	97	0,2	1,5
2016-07-11	29	12,3	21,3	28,0	73,8	47	99	0,4	1,4
2016-07-12	30,5	16,8	24,5	26,2	59,9	46	82	0	1,4
2016-07-13	34,1	19,1	27,8	24,2	63,7	53	76	0	2,1
2016-07-14	29	23,4	26,3	14,0	75,3	62	93	0	2,2
2016-07-15	29,6	18,6	23,2	20,9	75,4	49	92	0	2,1
2016-07-16	25,6	15,5	21	24,8	69,8	55	91	0	1
2016-07-17	27,6	18,4	23	24,5	62,6	45	82	7,4	1,3
2016-07-18	29,5	18	23,9	22,3	63,8	45	86	16,8	1,9
2016-07-19	24,5	13,7	19,4	23,8	55	35	78	0,6	1,3
2016-07-20	27,2	14,4	21,2	24,8	57	39	79	0	1,7
2016-07-21	31,1	18	24,8	25,6	59,6	46	76	0	2,7
2016-07-22	32,3	21,3	26,5	22,4	63,6	40	89	5,2	2,4

2016-07-23	28,5	19,1	22,5	12,9	81,5	67	95	2,4	1,2
2016-07-24	27,3	12,6	21,2	25,2	62,5	48	82	0	0,9
2016-07-25	26,4	17,3	22,5	7,0	80,2	70	91	3,4	0,9
2016-07-26	28,5	19,8	23,7	20,8	72,7	52	96	0	1,4
2016-07-27	30,8	19	25,3	25,5	66,6	39	91	0	1,9
2016-07-28	28,9	18,4	23,7	17,5	61,1	48	78	0	0,6
2016-07-29	27,9	15	21,6	23,1	57,8	45	76	3,6	0,6
2016-07-30	28,1	15,3	21,9	25,3	55,5	42	71	0	0,7
2016-07-31	29,9	15,1	23	26,0	56	36	86	0	0,9
2016-08-01	29,3	18,5	23	20,2	65,8	52	78	0	1,5
2016-08-02	30,7	17,6	23,7	25,9	57,3	32	77	0	1
2016-08-03	31,3	15,7	24,6	25,7	60,3	34	89	0	1,2
2016-08-04	32,4	20,6	27	23,9	58,5	41	73	5	1,9
2016-08-05	33,9	21,9	28,3	23,4	59,7	37	81	0	2,7
2016-08-06	29	19	24,4	21,7	59,9	36	89	0,2	1,6
2016-08-07	28,4	16,5	21,8	22,0	55,5	42	72	0,4	1,5
2016-08-08	29,5	16,1	22,1	22,7	53	34	78	0	1,2
2016-08-09	30,9	11,3	22,4	24,0	48,8	34	76	0	0,9
2016-08-10	33,2	17,8	26,3	20,2	60,7	45	75	0	1,6
2016-08-11	32,8	22,9	27,7	19,5	64,4	50	81	0	1,3
2016-08-12	28,6	18,5	21,4	6,7	81,8	69	91	6,8	1,8
2016-08-13	21,1	16,7	19,4	4,7	90,8	83	96	16,6	1,6
2016-08-14	26,2	17,4	20,8	10,5	83,8	63	97	16	1,3
2016-08-15	28,7	17,1	23,1	23,5	68,8	51	90	0	1,1
2016-08-16	26,6	17,8	21,2	7,1	84,8	64	96	75,6	1,6
2016-08-17	28,1	17	22,6	22,2	72	51	94	6,2	1,7
2016-08-18	28,4	17,2	23,3	22,3	67,7	48	86	0,4	1,2
2016-08-19	28,9	14,4	22,7	24,1	63,3	47	88	0	0,8
2016-08-20	31,3	16,1	24,9	21,8	62,2	43	81	0	1,5
2016-08-21	28,4	20,5	23,9	7,4	77,3	57	93	19,8	2,7
2016-08-22	23	13,5	18,2	18,5	62,5	43	82	0	1,7
2016-08-23	27	12,7	20,5	23,6	66	49	88	0	2,5
2016-08-24	29,6	18,4	24,5	22,1	66,9	50	83	0	2,1
2016-08-25	27,4	22,7	24,8	8,9	78,9	71	94	0,8	1,9
2016-08-26	29,4	18,8	24,9	22,0	67,5	44	91	0	1,6
2016-08-27	27,7	16,1	22	22,9	61,6	46	81	0	0,9
2016-08-28	29,1	18,9	23,4	12,9	74,3	64	90	0	1,1
2016-08-29	27,4	16,8	22,3	20,7	63,3	45	88	0	1,1
2016-08-30	26,9	15,4	21,4	14,4	70,7	53	85	0	1,5
2016-08-31	27,7	19,5	22,7	13,7	80	68	93	0,2	1,5
2016-09-01	24,9	13,1	18,9	16,9	70,3	53	87	0	0,6

2016-09-02	23,6	11,8	17,6	16,2	63,1	51	77	0,2	0,5
2016-09-03	25,4	9,9	17,3	20,9	67,3	52	88	0	0,5
2016-09-04	27,8	11,1	19,1	20,0	66,3	34	92	0	0,5
2016-09-05	29,5	11,7	20,3	21,5	70,3	43	94	0	0,6
2016-09-06	29,9	13,2	21,7	20,9	69,7	44	93	0	0,6
2016-09-07	31,1	15,1	23,7	18,4	69,5	53	87	5,4	1
2016-09-08	26,1	21,6	23,5	3,9	88,7	78	96	13,4	0,7
2016-09-09	28,6	19,5	24	20,5	70,5	50	91	0	1,8
2016-09-10	28,7	15,6	23,2	12,6	73,3	58	90	0	1,8
2016-09-11	25,6	12,9	18,8	11,6	66,5	48	91	8	2,6
2016-09-12	24,4	10,1	17,9	19,7	64,6	45	82	0	1,8
2016-09-13	27,5	11,9	20,9	19,3	62,9	41	79	0	2
2016-09-14	21,7	9,9	18,7	11,1	64,2	49	87	0	1,3
2016-09-15	20,1	6,2	12,9	19,6	63,8	46	86	0	0,6
2016-09-16	22,5	6,3	14,4	19,4	65,8	40	93	0	0,5
2016-09-17	24,6	10,1	18,2	10,6	74	56	89	1,4	1,4
2016-09-18	27,5	20,3	23,2	15,7	78,8	57	95	1,6	2,1
2016-09-19	28	16,6	22,3	15,9	75,5	58	90	0	1
2016-09-20	27,4	15,4	20,2	13,6	74,4	50	95	0	1,3
2016-09-21	26,9	13,9	20,1	17,4	60,9	39	81	0	1,7
2016-09-22	21,1	12,2	17,2	9,7	64,4	48	89	0,8	1,8
2016-09-23	21,1	7,5	13,8	14,6	70	46	91	1,6	0,8
2016-09-24	19,3	5,2	11,5	18,4	55,7	33	88	0	0,8
2016-09-25	19,6	5,1	11,3	18,3	54	30	79	0	0,9
2016-09-26	19,2	3,3	12,6	14,5	65,1	39	93	0	1,3
2016-09-27	22,2	11,9	16,4	13,5	71,8	43	94	2,6	1,4
2016-09-28	21,3	11	14,6	12,9	78	61	92	0	2,6
2016-09-29	19,1	8,2	13,2	16,8	67	46	85	0	2,7
2016-09-30	20,1	8,1	13,8	13,5	67	48	89	0	1,9
2016-10-01	20	11,7	15,4	9,2	66,8	44	85	0	1,5
2016-10-02	17,2	12,9	14,6	4,2	83,2	70	97	0,2	1
2016-10-03	21,3	10,9	15,6	12,7	78,2	56	97	0,2	1,3
2016-10-04	21,6	6,2	12,4	14,6	67,5	46	88	0	1
2016-10-05	23,3	5,9	13,7	15,1	75,5	50	92	0	0,4
2016-10-06	24,4	7	15,3	14,8	73,6	45	95	0	0,8
2016-10-07	26,2	8,6	17,7	14,8	69,6	39	96	0	1
2016-10-08	18,4	11,9	15,9	1,7	84,2	66	95	15	1,4
2016-10-09	15,8	5,8	10,9	9,0	66,3	47	93	0	0,7
2016-10-10	13,6	2,4	7,8	15,1	58,5	41	73	0,2	1
2016-10-11	18,5	3	9,8	14,5	60	37	84	0	0,9
2016-10-12	21,6	4,8	13,6	12,4	56	38	70	0	0,9

2016-10-13	15	3,2	11,6	2,5	75,6	65	93	7,8	1,9
2016-10-14	12,6	-0,4	5,7	13,0	62,8	39	87	0	0,7
2016-10-15	17	0,1	9,4	13,4	61,4	43	86	0	1,1
2016-10-16	18,8	11,4	14,6	2,1	81,7	57	96	6,4	1,3
2016-10-17	16,6	8,5	12,5	12,3	70,8	53	98	0,2	1,5
2016-10-18	25,2	8,4	15	6,5	78,5	59	93	6,8	2,2
2016-10-19	18,7	6,7	13,9	12,0	69,3	47	90	0,2	1,3
2016-10-20	11,5	4,6	9,1	2,2	87,3	75	94	16,4	1,2
2016-10-21	11	8,5	10,1	1,4	93,3	85	96	42,6	1,9
2016-10-22	9,1	3,1	7,4	2,4	92,8	89	95	29,4	1,5
2016-10-23	11,7	3,1	6,8	10,1	64,7	37	90	7,2	3,6
2016-10-24	8,6	3,6	5,9	7,3	62,1	52	76	0	2,4
2016-10-25	8,2	0,4	4,5	6,7	58,5	45	75	0	1,7
2016-10-26	4,6	-2,3	1,8	4,9	63,7	51	81	0	0,6
2016-10-27	7,2	-0,7	2,5	5,6	74,3	52	91	10,4	2,1
2016-10-28	6,2	3,1	4,7	2,4	91	86	95	7,6	1,3
2016-10-29	6,9	3,7	5,4	0,9	91,8	84	97	8	1,4
2016-10-30	7,4	4,7	6,1	3,6	75	65	90	0	0,8
2016-10-31	6,3	2,7	4,3	4,9	67,1	56	79	0	0,8
2016-11-01	11,4	-1,3	5,9	5,5	68,3	56	83	0	1,4
2016-11-02	16,9	6,8	11,2	6,9	79,8	71	92	0	0,9
2016-11-03	12,2	7,9	9,7	1,6	89,7	75	95	7,2	0,7
2016-11-04	8	1,7	4	6,8	71,4	56	89	1,8	1,2
2016-11-05	9,3	1,5	5,7	2,6	84,4	75	94	0,6	0,9
2016-11-06	11,4	-1,3	5,3	9,1	69,7	47	92	0,2	0,8
2016-11-07	12,2	-3,6	4,6	9,9	75,6	54	91	0	0,9
2016-11-08	17,1	1,3	10	9,1	68,7	43	91	0	1
2016-11-09	11,5	-0,5	7,3	8,1	68,3	47	87	0,4	0,9
2016-11-10	12,8	-2,4	5,7	5,0	69,4	59	86	0	2,5
2016-11-11	12,7	-0,8	5,9	4,8	54,8	40	81	0,8	2,4
2016-11-12	8,6	-2	3,1	6,9	59,6	48	73	2,8	3,1
2016-11-13	12,8	6,9	9,2	8,7	63,8	53	79	0,6	3,5
2016-11-14	14,6	3,6	9,2	8,4	64,8	48	82	0	2
2016-11-15	13,5	1,9	7,2	6,6	78,3	58	90	0	1,2
2016-11-16	8,6	6,3	7,6	1,2	92,6	89	95	2,4	1,5
2016-11-17	12,6	2	7,2	6,1	85,1	66	94	0,2	1
2016-11-18	9	-0,5	3,8	4,2	93,7	80	98	0	1
2016-11-19	11,6	3,2	6	4,4	87,5	72	97	0	2,1
2016-11-20	8,4	0,6	3,8	1,0	90,2	73	96	12,4	2,1
2016-11-21	0,8	-1,6	-0,5	3,3	86,6	80	92	0,6	3,3
2016-11-22	0,7	-1,3	-0,3	3,0	71,4	65	81	0	2,7

2016-11-23	3,3	-2,2	0,2	6,6	78,9	75	84	0,2	1,9
2016-11-24	0,9	-0,6	0,2	1,6	86	75	94	0	1,8
2016-11-25	1,3	0,3	0,8	0,9	95,8	93	97	3,8	1
2016-11-26	3,1	1,1	1,9	1,6	92,5	82	98	2,4	0,8
2016-11-27	3,9	-0,3	1,3	3,6	79,6	68	92	0	1,2
2016-11-28	0,6	-1,8	-0,5	2,7	72,8	67	82	0	1,1
2016-11-29	2	-1,6	0,4	0,4	90,3	80	97	12,2	2
2016-11-30	7	1,6	3,1	0,9	96	89	98	7,8	2,3
2017-05-15	24,75	9,53	15,49	19,9	60,1667	31,0	92	1	1,49
2017-05-16	24,18	10,73	17,43	28,5	56,6667	35,0	84	0	1,93
2017-05-17	31,23	15,39	22,03	24,1	55,75	42,0	71	5	2,51
2017-05-18	32,03	21,62	26,51	25,2	55,2083	38,0	78	12,2	3,86
2017-05-19	27,86	12,08	18,07	23,8	53,0417	26,0	76	0,4	1,99
2017-05-20	21,09	5,588	12,59	30,5	40,4167	26,0	57	0	1,38
2017-05-21	21,87	7,882	14,61	18,0	36,0417	19,0	73	0	1,56
2017-05-22	18,13	10,52	12,89	4,4	90,8333	80,0	96	5	2,1
2017-05-23	21,91	11	15,74	22,9	63,75	46,0	84	0,2	2,16
2017-05-24	26,33	10,97	18,25	21,4	58,6667	35,0	91	0	0,92
2017-05-25	22,77	12,79	17,07	8,3	69	40,0	92	4	2,38
2017-05-26	15,35	12,48	13,71	5,5	82,625	62,0	93	20,8	3,25
2017-05-27	24,23	11,33	16,87	24,2	67,5833	42,0	95	0	0,77
2017-05-28	27,16	13,5	20,41	27,8	58,5417	29,0	83	0	1,41
2017-05-29	14,85	13,84	14,3	0,9	78,7083	56,0	95	1,4	3,36
2017-05-30	19,12	13,24	15,41	12,9	87,2083	79,0	95	8,8	2,18
2017-05-31	24,22	13,34	17,97	22,7	68,7083	33,0	96	4,8	2,12
2017-06-01	19,35	13,76	16,41	22,9	59,5833	40,0	76	1	2,63
2017-06-02	16,86	8,46	12,4	16,8	74	53,0	91	0,8	1,6
2017-06-03	19,94	10,28	13,24	13,7	74,5833	60,0	87	0,8	1,32
2017-06-04	24,28	10,55	17,19	22,9	68,2083	45,0	90	0	1,11
2017-06-05	17,74	13,81	15,22	4,5	86,2083	70,0	96	17,8	1,8
2017-06-06	17,43	11,57	13,29	7,0	83,125	65,0	94	29,6	2,83
2017-06-07	27,1	8,7	17,29	30,0	67,0833	45,0	96	0	1,62
2017-06-08	29,46	14,51	21,8	28,4	58,125	38,0	77	0	2,04
2017-06-09	26,7	18,61	22,5	19,4	53	36,0	74	0,2	1,9
2017-06-10	26,16	8,49	18,4	26,1	53,1667	33,0	80	0	0,98
2017-06-11	31,04	21,72	26,2	28,6	54,5	43,0	74	4,2	4
2017-06-12	32,97	20,81	26,69	22,7	59	46,0	88	5,2	2,59
2017-06-13	29,36	22,15	25,53	24,3	49,7083	31,0	77	0	1,57
2017-06-14	24,93	12,12	17,84	31,1	41,5	33,0	52	0	1
2017-06-15	25,14	10,62	18,08	28,2	40,6667	26,0	61	0	1,71
2017-06-16	21,18	13,96	17,55	3,7	84,8696	58,0	96	20,2	2,16

2017-06-17	28,62	15,25	21,37	16,4	74,8333	58,0	89	1,6	0,8
2017-06-18	33,15	21,17	26,96	26,0	69,9583	49,0	88	0,6	2,27
2017-06-19	30,82	22,12	25,1	16,2	71,7083	57,0	88	0,2	2,99
2017-06-20	25,28	17,68	21,31	16,0	72,625	55,0	95	5,8	2,26
2017-06-21	23,49	16,1	19,52	18,3	69,4167	40,0	87	1	2,71
2017-06-22	25,4	14,48	19,95	21,4	65,375	40,0	90	0	1,59
2017-06-23	26,94	17,44	21,29	11,2	88,2083	64,0	97	12,2	1,62
2017-06-24	27,43	18,45	22,53	25,3	71,9583	43,0	95	0,6	1,49
2017-06-25	24,77	15,59	19,43	20,9	74,625	48,0	88	0	1,29
2017-06-26	23,25	13,98	18,03	31,2	59,7917	35,0	94	1	1,43
2017-06-27	22,32	14,86	17,75	18,1	74,25	56,0	86	0	1,65
2017-06-28	23,18	13,26	17,82	24,5	73	50,0	91	0,2	1,82
2017-06-29	22,08	14,21	17,9	13,0	78,7083	60,0	95	1,8	1,8
2017-06-30	23,38	16,14	18,67	6,6	91,5833	86,0	96	2,8	1,06
2017-07-01	24,6	20,24	22,17	6,5	90,75	83,0	97	4,4	0,78
2017-07-02	24,97	18,46	21,04	19,1	79,5	62,0	91	1,2	2,38
2017-07-03	26,02	16,93	21,01	25,8	67,5833	45,0	91	0,2	2,19
2017-07-04	28,35	13,13	21,14	26,1	58,125	35,0	89	0	0,67
2017-07-05	29,1	12,72	22,06	29,8	52,3333	25,0	85	0	0,94
2017-07-06	30,2	16,1	23,91	25,1	66,3333	57,0	80	0	1,95
2017-07-07	27,56	20,47	24,5	14,6	78,0417	62,0	90	3,2	1,84
2017-07-08	25,14	17,34	20,81	13,6	81,4583	61,0	96	33,8	0,83
2017-07-09	26,29	14,92	20,25	23,3	70,7917	54,0	88	0	2
2017-07-10	25,21	18,09	21,05	16,1	76,5833	60,0	95	0,8	2,06
2017-07-11	28,45	19,3	23,15	18,0	72,875	60,0	82	0,2	2,07
2017-07-12	23,77	16,63	19,54	12,2	61,0526	40,0	89	0	1,57
2017-07-13	24,71	14,62	18,56	23,3	64,5417	46,0	83	3	1,67
2017-07-14	23,24	13,9	18,54	10,9	82,75	65,0	90	13,8	1,21
2017-07-15	28,28	17,79	21,36	18,7	80,4583	56,0	98	7,8	1,22
2017-07-16	28,13	19,63	23,73	22,7	72,4167	57,0	88	0	1,73
2017-07-17	27,38	18,53	22,18	14,1	76,75	58,0	90	4,6	0,91
2017-07-18	29,9	16,4	23,6	27,2	75,5417	53,0	97	0	1
2017-07-19	28,11	20,57	24,66	16,0	75,2083	62,0	93	0	1,92
2017-07-20	28,64	18,2	23,42	17,2	81,375	60,0	99	0	1,11
2017-07-21	28,98	18,44	23,33	23,5	68,7917	53,0	80	10,8	1,92
2017-07-22	26,25	15,99	21,13	26,6	54,3333	43,0	78	0,2	0,9
2017-07-23	26,06	14,64	20,14	27,2	42,4583	29,0	63	0	1,18
2017-07-24	23,65	15,02	17,44	3,1	75,3333	39,0	95	13,4	1,91
2017-07-25	25,75	14,31	18,01	22,4	74,625	52,0	94	5,8	1,86
2017-07-26	24,97	13,8	19,72	17,9	75,3333	62,0	92	0	1,21
2017-07-27	26,79	18,65	22,08	17,3	76,8333	58,0	93	0	1,88

2017-07-28	26,09	12,42	19,8	26,2	62,6667	41,0	90	0	0,62
2017-07-29	26,33	10,02	18,55	28,4	54,125	28,0	79	0	0,94
2017-07-30	28,04	11,28	20,18	27,3	62,2083	45,0	89	0	1,06
2017-07-31	29,86	20,13	23,95	23,1	72,7917	52,0	96	25,6	1,36
2017-08-01	29,28	14,01	22,08	26,7	61,0833	39,0	94	0,2	0,67
2017-08-02	31,09	16,56	24,41	25,3	66,375	46,0	84	0	1,31
2017-08-03	30,27	17,64	23,88	20,4	72,4583	55,0	91	19,4	0,83
2017-08-04	29,83	18,81	23,68	18,1	79,6667	63,0	94	2,8	1,51
2017-08-05	26,02	19,32	22,03	16,3	77,5417	53,0	95	25,6	2,73
2017-08-06	22,35	13,83	18,12	21,7	66,4583	50,0	83	0,4	2,71
2017-08-07	25,35	13,67	17,93	18,8	68,6364	55,0	80	0	0,65
2017-08-08	25,14	13,8	19,22	25,0	63,25	37,0	86	0	1,15
2017-08-09	25,01	18,12	21,22	24,3	62,8333	46,0	83	0	2,04
2017-08-10	26,8	15,18	20,49	17,9	63,5417	50,0	80	0,4	0,69
2017-08-11	29,62	16,29	22,79	22,1	67,7083	41,0	90	0,2	0,97
2017-08-12	27,03	18,44	21,98	13,8	78,25	64,0	96	9,4	1,31
2017-08-13	27,57	17,27	21,68	25,5	66,25	41,0	95	5,4	1,55
2017-08-14	27,39	16,97	22,18	23,6	66,5417	48,0	86	0	1,73
2017-08-15	26,7	18,19	22,08	15,7	79,375	67,0	95	8,8	1,16
2017-08-16	23,79	12,95	19,53	24,2	59,6667	38,0	91	0	1,08
2017-08-17	26,65	14,51	20,03	21,7	62,7083	44,0	81	0	1,17
2017-08-18	22,8	17,17	19,82	5,7	84	60,0	96	14,8	1,39
2017-08-19	27,64	17,34	21,7	16,3	77,0833	57,0	98	0	1,72
2017-08-20	26,75	17,91	22,3	22,9	70,0417	52,0	87	0	2,14
2017-08-21	28,9	19,03	23,68	19,7	70,7917	52,0	88	0	2,1
2017-08-22	26,55	20,66	23,5	6,9	81,7083	73,0	89	24,4	1,78
2017-08-23	23,38	17,53	20,63	18,7	69,875	50,0	85	0,4	3,04
2017-08-24	22,32	13,97	17,72	19,5	71,4167	43,0	90	0	1,3
2017-08-25	23,12	11,14	16,43	20,5	66,9583	42,0	88	0	0,92
2017-08-26	23,1	9,11	15,99	16,1	61,8333	41,0	89	0	0,52
2017-08-27	24,7	8,91	16,83	20,1	60,3333	39,0	86	0	0,5
2017-08-28	25,79	9,18	17,24	22,5	59,7083	35,0	86	0	0,87
2017-08-29	25,72	13,33	18,75	16,0	58,375	38,0	80	0	0,82
2017-08-30	25,28	11,7	19,33	21,4	61,2083	44,0	79	0	1,09
2017-08-31	21,28	11,96	17,68	12,9	67,7083	50,0	90	1,6	1,24
2017-09-01	18,91	7,171	12,23	20,3	61,7083	40,0	80	0	1,74
2017-09-02	22,76	5,685	14,22	22,7	59,25	36,0	85	0	0,86
2017-09-03	18,89	10,39	12,93	2,3	87,4167	56,0	97	22,4	1,37
2017-09-04	24,41	13,2	17,17	8,2	79,0417	51,0	95	0,6	2,09
2017-09-05	20,76	17,71	19,49	9,0	81,125	68,0	92	7,2	1,43
2017-09-06	19,21	15,06	17,08	3,8	86,0417	80,0	92	0	0,7

2017-09-07	20,67	14,82	16,52	8,5	87,0417	72,0	97	7	0,96
2017-09-08	19,39	12,73	15,06	12,2	82,1667	62,0	93	0	1,57
2017-09-09	22,9	12,21	15,72	13,6	71,375	48,0	97	0,2	0,64
2017-09-10	21,65	6,766	13,62	17,8	67,7917	43,0	90	0	0,71
2017-09-11	24,16	8,43	16,5	19,1	69,2083	43,0	87	0	1,03
2017-09-12	25,48	13	18,65	19,7	69,4583	51,0	86	0	1,69
2017-09-13	26,9	14,11	20,22	18,6	70,9583	52,0	87	0	1,4
2017-09-14	29,29	15,79	21,85	18,2	71,5	52,0	88	0	0,64
2017-09-15	28,48	16,13	20,98	17,2	73,7917	53,0	93	0	0,78
2017-09-16	28,15	15,79	20,99	15,6	82,0417	60,0	98	0	0,91
2017-09-17	29,25	18,02	23,15	17,6	74,25	52,0	92	0	1,13
2017-09-18	27,99	15,85	20,91	12,9	80,25	55,0	99	0	0,94
2017-09-19	30,18	16,3	22,49	14,4	73	56,0	90	0	0,84
2017-09-20	28,25	17,91	21,9	15,1	76,9583	58,0	98	0	1,36
2017-09-21	27,58	14,18	20,4	18,1	56,875	31	80	0	1,31
2017-09-22	28,62	12,63	19,37	17,3	64,1667	40	87	0	0,71
2017-09-23	31,01	14,78	21,79	16,4	71,5417	51	91	0	1,05
2017-09-24	32,79	19,42	25,47	16,2	71,8333	61	84	0	1,36
2017-09-25	33,63	21,37	26,68	16,5	70,875	44	91	0	1,19
2017-09-26	32,3	21,44	26,06	13,7	73,9167	54	94	0	1,01
2017-09-27	32,21	21,34	25,23	0,5	75,2917	43	97	6,4	2,63
2017-09-28	22,86	11,3	16,44	16,5	60,6667	45	76	0	1,43
2017-09-29	16,89	4,771	11,02	13,5	62	45	89	0	0,75
2017-09-30	17,4	5,889	11,94	17,0	53,375	35	76	0	1,12
2017-10-01	18,94	3,959	11,36	16,9	61,25	37	84	0	1,36
2017-10-02	21,62	5,992	13,72	15,8	63,0417	37	89	0	0,72
2017-10-03	24,08	6,06	14,56	15,7	66,3913	43	89	0	1,2
2017-10-04	26,34	13,54	19,26	9,8	72,9583	50	92	11	2,14
2017-10-05	20,44	11,98	16,71	8,1	74,7083	45	98	4,8	1,65
2017-10-06	20,91	10,97	15,71	13,3	75,2083	52	93	0	1,33
2017-10-07	20,96	8,87	13,66	4,4	88,625	82	97	5,4	0,83
2017-10-08	24,67	19,3	21,31	7,4	75,0833	58	94	10,4	2,59
2017-10-09	20,57	14,62	17,33	1,7	92,2083	81	97	27,4	0,86
2017-10-10	22,49	14,45	17,45	10,5	86,9167	67	98	0,2	1,36
2017-10-11	18,11	6,806	10,94	8,5	60,3333	51	73	0	0,7
2017-10-12	17,63	2,132	9,56	14,4	55,9167	34	83	0	1,02
2017-10-13	18,58	2,57	10,66	11,2	62,5833	43	91	0	1,25
2017-10-14	19,55	14,18	16,53	3,4	83,5833	64	91	0	1,45
2017-10-15	24,72	14,48	17,52	1,4	86,7083	68	97	17	1,7
2017-10-16	18,19	4,8	9,13	5,8	67,875	55	79	0,2	1,42
2017-10-17	14,67	-0,81	6,222	6,4	66,9167	48	92	0	1,67

2017-10-18	19,2	10,25	16,51	12,7	70,25	46	88	0	1,65
2017-10-19	21,16	6,501	15,19	10,1	64,087	44	88	15,6	2,62
2017-10-20	18,48	7,735	13,38	12,6	52,9583	36	70	0	1,88
2017-10-21	21,62	6,382	13,58	11,2	63,8333	49	88	0	0,77
2017-10-22	19,92	7,941	12,82	9,5	77,375	57	91	0	0,88
2017-10-23	22,7	5,399	13,35	10,7	71,875	43	91	0	1,14
2017-10-24	23,59	15,07	17,95	2,3	84,125	61	98	30	1,96
2017-10-25	18,12	10,93	13,96	10,3	72,6667	43	99	0,4	0,94
2017-10-26	12,94	8,27	10,44	2,9	73,875	62	83	0,8	0,67
2017-10-27	11,01	4,765	8,18	9,4	72,75	60	86	0,6	1,91
2017-10-28	19,2	3,603	10,28	10,2	69,6667	51	94	0	1,65
2017-10-29	17,49	8,27	11,28	0,8	90,875	78	96	20,2	1,36
2017-10-30	18,65	7,691	11,49	3,1	77,0417	48	95	108	5,04
2017-10-31	11,17	6,476	8,21	6,8	65,7083	44	84	2,2	4,31
2017-11-01	9,77	-0,24	4,739	4,1	76	53	90	0,2	0,92
2017-11-02	13,8	5,196	8,04	0,8	94,375	83	97	24,8	1,11
2017-11-03	16,79	6,499	12,66	4,8	74,3333	53	97	13,2	2,26
2017-11-04	7,194	-1,75	3,428	7,5	74,4167	55	91	0	0,82
2017-11-05	11,53	1,976	5,758	1,1	82,9167	67	93	11,4	2,82
2017-11-06	14,61	3,653	11,52	4,7	80,9167	62	98	6	2,33
2017-11-07	4,966	-0,77	2,511	8,8	60	46	74	0	1,09
2017-11-08	6,669	-3,17	1,776	4,6	62,4167	45	79	0	1,13
2017-11-09	8,58	-1,19	4,476	4,5	65,125	51	85	0	1,86
2018-05-10	25,4	17,0	19,6	8,2	56,7	41	75	0,4	3,2
2018-05-11	17,2	3,0	8,4	26,1	44,7	29	59	0	2,1
2018-05-12	18,2	1,4	10,1	27,6	41,3	23	77	0	0,9
2018-05-13	22,3	5,0	14,2	29,0	42,4	19	84	0	1,2
2018-05-14	26,3	12,5	18,8	28,8	48,3	20	76	0	3,0
2018-05-15	22,4	15,0	17,8	10,3	59,8	21	93	1,2	2,4
2018-05-16	23,3	3,8	12,7	28,6	43,6	36	60	0	1,9
2018-05-17	22,0	11,5	16,3	23,2	52,7	37	84	0	2,4
2018-05-18	17,4	2,7	10,9	29,6	33,8	22	50	0	1,5
2018-05-19	20,1	5,7	11,9	13,9	60,8	23	94	5,8	2,0
2018-05-20	21,7	11,4	15,6	21,3	69,5	31	98	9,2	1,5
2018-05-21	26,2	8,5	17,0	28,2	49,6	27	79	0	1,9
2018-05-22	23,7	13,9	17,9	11,3	67,3	43	98	2,6	1,3
2018-05-23	24,9	11,4	16,7	19,6	63,4	19	98	0	1,4
2018-05-24	24,3	11,0	16,4	26,5	33,0	25	56	0	1,2
2018-05-25	26,9	16,1	21,1	20,7	60,4	47	82	0,6	3,1
2018-05-26	24,1	16,5	19,7	15,7	66,0	25	97	7,8	1,8
2018-05-27	20,7	11,6	15,6	7,2	65,8	47	87	0,4	2,3

2018-05-28	22,4	14,0	17,0	10,3	75,9	62	93	2	1,6
2018-05-29	27,3	14,3	20,8	30,3	58,0	25	99	0	1,0
2018-05-30	31,1	9,8	19,6	27,6	49,5	31	74	0	1,3
2018-05-31	31,1	19,8	25,4	23,6	61,0	44	75	0,4	1,7
2018-06-01	30,7	21,9	25,5	18,2	72,7	60	89	0	1,6
2018-06-02	27,0	14,5	20,8	30,5	46,9	25	70	0	1,6
2018-06-03	25,3	10,8	18,1	30,9	42,5	24	74	5	2,8
2018-06-04	21,3	8,5	12,7	4,1	89,3	79	96	23	2,7
2018-06-05	16,7	10,5	13,4	16,2	81,5	72	96	0,6	2,0
2018-06-06	18,4	10,8	13,5	12,7	78,3	62	96	0	1,2
2018-06-07	21,3	12,8	16,2	18,9	69,5	51	92	0	2,3
2018-06-08	23,0	11,9	17,9	30,4	50,4	32	82	0	1,3
2018-06-09	23,7	12,3	18,3	29,5	42,8	20	75	0	1,0
2018-06-10	22,0	7,0	15,1	28,2	42,5	29	68	0	0,8
2018-06-11	24,6	6,7	16,6	31,2	40,4	24	68	0	1,0
2018-06-12	27,5	9,7	19,8	28,5	47,2	34	70	0	2,2
2018-06-13	25,7	18,2	21,4	12,9	72,7	55	97	4,6	1,6
2018-06-14	19,7	13,3	16,1	7,6	87,9	80	96	10,4	2,0
2018-06-15	26,3	10,9	17,0	29,1	69,0	39	94	0,2	1,4
2018-06-16	28,6	14,8	21,6	28,8	54,8	28	83	0	1,5
2018-06-17	29,6	16,9	23,5	24,3	55,4	44	71	0,8	1,8
2018-06-18	29,0	20,5	24,3	13,9	83,2	68	95	19	2,0
2018-06-19	25,3	12,5	19,6	31,2	56,2	30	85	0	0,9
2018-06-20	27,9	12,5	19,9	26,0	65,4	49	83	0,8	1,8
2018-06-21	22,6	11,0	17,4	31,5	49,6	37	77	0	1,1
2018-06-22	26,6	8,5	17,8	30,3	47,1	26	80	0	0,8
2018-06-23	23,1	13,4	18,5	11,5	65,4	45	92	4	1,1
2018-06-24	24,4	14,8	17,4	16,0	87,6	69	97	5,4	0,9
2018-06-25	23,4	9,9	16,9	31,3	50,3	25	93	0	0,6
2018-06-26	24,8	8,1	16,9	30,0	50,0	33	71	0	1,0
2018-06-27	27,9	14,6	21,5	20,0	66,3	48	97	2,2	1,1
2018-06-28	23,8	17,1	20,3	12,9	84,9	73	97	0,2	1,2
2018-06-29	31,7	19,0	24,0	26,5	67,8	36	97	0	1,7
2018-06-30	32,2	22,2	26,4	21,2	65,1	55	91	5,8	2,1
2018-07-01	35,1	23,6	28,8	22,2	76,2	51	97	0	1,0
2018-07-02	36,1	21,7	29,4	27,1	68,3	45	93	0	1,9
2018-07-03	33,0	23,5	28,4	29,5	59,1	34	89	0	1,5
2018-07-04	34,7	19,1	27,8	28,8	57,5	35	91	0	1,1
2018-07-05	35,3	22,2	29,1	27,8	65,0	48	88	0	1,7
2018-07-06	31,8	18,5	23,4	23,9	55,7	38	80		1,6
2018-07-07	28,1	11,3	19,6	29,8	48,5	30	72	0	1,5

2018-07-08	29,3	17,8	23,7	28,6	47,0	34	61	0	2,8
2018-07-09	32,5	19,6	25,4	28,4	47,7	28	70	0	3,1
2018-07-10	30,6	21,1	25,7	25,2	51,8	31	74	0	1,4
2018-07-11	26,7	12,4	20,0	26,1	41,5	30	56	0	0,6
2018-07-12	29,0	14,4	21,8	29,1	50,3	33	73	0	0,8
2018-07-13	29,7	14,6	23,1	23,3	51,5	35	80	0	1,0
2018-07-14	29,3	20,5	25,2	17,6	67,1	53	86	0,4	1,5
2018-07-15	33,0	20,6	26,4	27,3	59,5	32	94	0	1,0
2018-07-16	34,0	17,0	26,4	23,2	53,3	35	81	0	1,0
2018-07-17	31,4	21,8	26,1	18,9	65,8	36	96	31,8	1,9
2018-07-18	25,1	12,1	19,7	30,0	45,3	30	66	0	1,0
2018-07-19	27,5	11,2	20,1	28,7	52,9	36	81	0	1,3
2018-07-20	31,6	17,2	24,8	28,6	50,0	28	77	0	1,2
2018-07-21	32,4	19,0	26,8	27,6	50,3	36	70	0	1,3
2018-07-22	29,8	17,7	21,9	10,9	67,3	48	87	5	2,0
2018-07-23	29,1	19,6	24,0	13,3	77,0	62	87	0	1,8
2018-07-24	29,7	23,7	25,9	13,4	78,3	59	94	1	2,5
2018-07-25	26,4	22,3	24,4	7,7	87,3	73	97	30,6	1,8
2018-07-26	28,9	21,4	24,0	17,5	82,0	57	98	26,8	1,2
2018-07-27	29,5	20,6	24,3	21,9	66,5	47	84	0,2	1,8
2018-07-28	26,8	18,9	22,7	23,2	70,1	48	90	1,8	1,6
2018-07-29	26,3	17,4	21,0	24,2	66,6	42	91	0	1,6
2018-07-30	28,5	17,5	22,7	26,5	61,7	43	81	0	1,7
2018-07-31	29,1	19,8	24,1	25,9	63,5	44	85	0	1,5
2018-08-01	28,6	23,2	25,5	26,7	73,7	63	95	3,6	1,6
2018-08-02	28,5	22,5	24,8	25,3	72,6	55	93	0	2,4
2018-08-03	28,2	21,5	24,7	20,4	76,2	66	84	0	1,2
2018-08-04	27,3	20,1	23,5	18,1	83,0	62	95	2,6	0,7
2018-08-05	31,5	17,7	24,7	16,3	72,1	47	94	0	1,0
2018-08-06	32,5	22,4	27,1	21,7	74,0	59	91	9,4	1,8
2018-08-07	28,2	21,4	24,8	18,8	81,3	63	93	1	3,9
2018-08-08	27,5	20,3	23,9	25,0	83,2	64	96	6	2,2
2018-08-09	27,4	19,6	23,5	24,3	79,7	53	96	3,6	4,4
2018-08-10	26,4	15,9	21,2	17,9	58,0	39	80	0	4,0
2018-08-11	27,4	16,0	21,7	22,1	59,3	38	82	0	2,7
2018-08-12	29,4	17,1	23,3	13,8	66,3	42	89	0	2,5
2018-08-13	29,6	20,4	25,0	25,5	70,7	53	88	0	2,2
2018-08-14	29,7	21,8	25,8	23,6	72,7	60	90	7,4	2,5
2018-08-15	27,5	21,2	24,4	15,7	76,8	55	94	0	3,6
2018-08-16	24,9	16,4	20,7	24,2	59,1	45	71	0	2,6
2018-08-17	23,9	16,5	20,2	21,7	83,5	72	95	3,6	3,6

2018-08-18	25,6	17,3	21,5	5,7	67,0	51	89	0	4,2
2018-08-19	28,1	15,8	22,0	16,3	62,1	40	90	0	2,9
2018-08-20	27,9	14,2	21,1	22,9	61,3	44	86	0	2,6
2018-08-21	27,1	17,6	22,4	19,7	66,0	48	80	0,4	5,2
2018-08-22	24,2	14,6	19,4	6,9	74,9	61	86	0,6	7,7
2018-08-23	25,5	11,6	18,6	18,7	60,0	37	81	0	4,8
2018-08-24	28,9	17,6	23,3	19,5	63,0	37	86	0	5,0
2018-08-25	30,3	16,5	23,4	20,5	57,5	36	78	0	3,3
2018-08-26	26,2	19,5	22,9	16,1	80,7	63	95	15,4	3,7
2018-08-27	26,3	18,3	22,3	20,1	79,7	65	95	3,6	3,2
2018-08-28	30,6	21,8	26,2	22,5	80,8	64	97	6,8	5,4
2018-08-29	31,6	21,2	26,4	16,0	82,2	61	95	1,8	4,2
2018-08-30	21,5	13,4	17,5	21,4	65,9	49	82	0	3,8
2018-08-31	24,5	10,5	17,5	12,9	62,7	47	87	0,4	4,0
2018-09-01	27,8	19,5	23,7	20,3	76,5	61	91	0	4,2
2018-09-02	25,4	19,5	22,5	22,7	87,5	74	95	10,4	3,7
2018-09-03	30,6	21,0	25,8	2,3	85,3	62	97	4,4	3,4
2018-09-04	26,6	17,8	22,2	8,2	61,6	36	97	0	2,8
2018-09-05	32,0	19,1	25,6	9,0	69,6	54	88	1,4	4,2
2018-09-06	26,3	15,2	20,8	3,8	62,3	38	81	0	4,1
2018-09-07	22,4	11,3	16,9	8,5	60,7	37	92	0	2,9
2018-09-08	17,9	9,3	13,6	12,2	53,5	40	67	0	4,0
2018-09-09	17,0	6,2	11,6	13,6	57,5	36	81	0	3,7
2018-09-10	18,1	7,9	13,0	17,8	67,0	42	94	17,6	5,0
2018-09-11	19,8	13,1	16,5	19,1	87,3	75	97	7,8	2,5
2018-09-12	24,6	15,1	19,9	19,7	76,4	55	93	0	1,3
2018-09-13	26,1	13,5	19,8	18,6	74,0	53	97	0	1,4
2018-09-14	28,3	15,5	21,9	18,2	66,7	32	95	0	2,2
2018-09-15	29,6	16,4	23,0	17,2	77,8	61	91	0	2,2
2018-09-16	27,6	18,9	23,3	15,6	74,9	58	94	0	2,8
2018-09-17	29,1	19,2	24,2	17,6	70,9	47	95	0	4,6
2018-09-18	26,6	11,8	19,2	12,9	78,8	64	88	0	4,6
2018-09-19	17,0	10,2	13,6	14,4	74,0	60	85	0	3,8
2018-09-20	17,0	9,1	13,1	15,1	78,0	61	95	0	3,1
2018-09-21	23,3	14,5	18,9	18,1	83,0	68	95	33,6	8,2
2018-09-22	18,7	8,1	13,4	17,3	56,0	43	75	0	5,4
2018-09-23	17,7	7,5	12,6	16,4	67,6	49	85	0	4,7
2018-09-24	14,9	4,2	9,6	16,2	52,5	29	77	0	5,0
2018-09-25	16,2	10,8	13,5	16,5	80,5	68	92	5,6	7,5
2018-09-26	23,4	12,0	17,7	13,7	83,5	65	93	3,8	5,5
2018-09-27	17,8	7,7	12,8	0,5	62,0	44	87	0	2,5

2018-09-28	20,8	12,1	16,5	16,5	72,4	58	87	1,2	4,2
2018-09-29	16,4	9,2	12,8	13,5	77,1	56	91	1,8	3,6
2018-09-30	12,1	7,9	10,0	17,0	78,8	60	93	1,2	3,4
2018-10-01	13,7	7,6	10,7	16,9	73,9	56	94	0,2	2,0
2018-10-02	10,8	7,6	9,2	15,8	90,8	65	96	8,8	5,7
2018-10-03	12,1	9,0	10,6	15,7	88,6	80	96	0	3,2
2018-10-04	24,6	6,5	15,6	9,8	75,9	48	93	0,2	6,1
2018-10-05	10,8	3,3	7,1	8,1	53,6	40	73	0	3,8
2018-10-06	11,5	6,3	8,9	13,3	70,1	50	95	0	3,9
2018-10-07	10,4	5,7	8,1	4,4	78,0	64	94	0	3,7
2018-10-08	10,9	6,0	8,5	7,4	80,0	62	95	18,8	4,8
2018-10-09	26,8	8,4	17,6	1,7	85,6	65	98	0,2	3,5
2018-10-10	21,8	8,6	15,2	10,5	91,0	85	97	5,4	5,6
2018-10-11	10,9	7,6	9,3	8,5	96,3	94	98	7,8	5,0
2018-10-12	11,2	6,3	8,8	14,4	64,1	45	98	0	5,6
2018-10-13	9,0	4,2	6,6	11,2	64,2	48	79	0	3,6
2018-10-14	12,8	3,5	8,2	3,4	63,9	49	81	0	3,9
2018-10-15	13,2	5,2	9,2	1,4	82,1	58	96	5,4	5,6
2018-10-16	8,7	3,8	6,3	5,8	61,3	51	73	0	7,9
2018-10-17	10,3	1,0	5,7	6,4	63,2	41	81	0,2	8,4
2018-10-18	5,2	-0,8	2,2	12,7	52,4	38	71	0	6,7
2018-10-19	15,8	4,7	10,3	10,1	61,4	54	75	0	7,5
2018-10-20	13,9	2,2	8,1	12,6	59,6	43	87	0,8	8,5
2018-10-21	4,9	-0,4	2,3	11,2	55,8	44	73	0	5,7
2018-10-22	6,3	-2,1	2,1	9,5	60,9	47	82	0,2	2,7
2018-10-23	9,4	0,0	4,7	10,7	73,4	61	88	0,6	5,2
2018-10-24	7,3	1,8	4,6	2,3	78,1	63	92	1	4,5
2018-10-25	3,4	-0,6	1,4	10,3	58,0	47	77	0	5,3
2018-10-26	5,2	-4,7	0,3	2,9	55,1	38	68	0	3,5
2018-10-27	5,2	-3,2	1,0	9,4	72,0	50	94	9	7,8
2018-10-28	4,5	0,8	2,7	10,2	93,2	90	97	6	5,0
2018-10-29				0,8	91,9	82	97		3,1
2018-10-30	4,7	-1,6	1,6	3,1	78,3	67	91	0	4,8
2018-10-31	4,6	-0,9	1,9	3,9	90,3	79	97	8,8	2,7