Microsieve Technology Applied to Lagoon Wastewater Treatment Facilities

By

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Abstract

Water resource recovery facilities such as wastewater treatment lagoons are under increased pressure to upgrade and improve their effluent quality due to increased loadings and increasingly stringent effluent targets and regulations. Lagoon technologies have inherent advantages for rural communities, however, this technology remains prone to effluent compliance issues. The upgrading of existing lagoons with economical, small footprint, low intensity technologies would enable rural communities to meet stringent regulations. A knowledge gap was identified with respect to economical, compatible, and appropriate technologies for the removal of solids from lagoon effluent, particularly with respect to modern microsieve technologies and their potential to guarantee solids effluent compliance of lagoon wastewater treatment systems. As such, the objective of this thesis is to study the performance of a microsieve technology, the discfilter system, as applied to lagoon wastewater treatment facilities and to study its potential to meet effluent solids concentration compliance. The study was performed at pilot scale, at the Casselman, ON, Canada lagoon wastewater treatment facility. The study quantified the solids removal performance of the discfilter system using various filter cloths at various hydraulic and solids loading rates. Moreover, the study determined related peripheral benefits of the discfilter system applied to lagoon facilities, specifically the removal of total phosphorus and algae from lagoon effluent.

Two filter materials with pore-sizes of 10 µm and 5 µm were investigated across various hydraulic loadings of 4.0 to 9.2 m/h and solids loadings of 15.7 to 574.1 g-TSS/m^2/h. The performance assessment highlighted a maximum hydraulic load of 6.85 m/h for the 5µm filter cloth, with the 10 µm filter cloth not showing hydraulic limitation within the applied hydraulic loadings of this study. The 10 µm filter cloth solids removal performance was dependent upon the operation of the upstream lagoon facility, particularly on the application of the aeration system. The 10 µm filter cloth demonstrated a solids removal performance that meets current federal Canadian total suspended solids concentration regulations (<25 mg/L) for all data sets studied during non-aerated operation of the final lagoon cell of the upstream lagoon facility. However, the 10 µm filter cloth showed susceptibility to changes in solids characteristics during aeration of the final

lagoon cell, with 80% of the total suspended solids concentration data being non-compliant (>25 mg/L). The solids removal performance of the 5 µm material achieved a high effluent total suspended solids quality (<10 mg/L) in all conditions. The assessment of peripheral benefits showed total phosphorus removal from influent concentrations of 0.3 to 0.8 mg-P/L to levels at or below 0.3 mg-P/L. In addition, the discfilter maintained an effluent algae/Chlorophyll α concentration of 7 µg-Chl.α/L or less for influent concentrations ranges of 4 to 24 µg-Chl.α/L.

Résumé

Les installations d'épuration d'eaux usées tels que les étangs font face à un besoin grandissant pour la mise-à-niveau et l'amélioration des installations afin d'accroître la qualité de leur effluent. Ce besoin survient en raison des taux de chargements grandissants ainsi qu'en raison de la mise en œuvre de normes de qualité de plus en plus strictes. L'utilisation des étangs d'eau usée comme technologie d'épuration d'eau a des avantages particuliers pour les communautés rurales, cependant, cette technologie est assujettie à des problèmes liés à la non-conformité des normes de l'effluent. La mise-à-niveau des installations existantes avec des technologies économes, compactes, et à faible intensité opérationnelle permettrait aux communautés rurales de satisfaire aux exigences pour le traitement des eaux usées. Il existe un écart des savoirs actuels quant aux technologies économes, compatibles, et appropriées pour la mise-à-niveau visant l'enlèvement des matières en suspension (MES) de l'effluent des étangs d'eaux usées. Ceci est particulièrement vrai en ce qui a trait à l'utilisation du micro-tamisage pour garantir la conformité de l'effluent des étangs d'eaux usées vis-à-vis les normes concernant les matières en suspension. L'objectif de cette étude est d'étudier la performance d'une technologie de micro-tamisage, le système *discfilter*, tel qu'appliqué aux étangs d'eaux usées, et, d'étudier leur potentiel pour assurer la conformité l'effluent de ces systèmes par rapport aux matières en suspension. L'étude a été effectuée à l'échelle pilote aux installations d'étangs de la municipalité de Casselman, ON, Canada, et a quantifié la performance du système *discfilter* vis-à-vis l'enlèvement des matières en suspension par rapport aux toiles de filtrations, au chargement hydraulique et au chargement des matières en suspension. De plus, l'étude a déterminé des avantages secondaires du système *discfilter* appliqué aux étangs, particulièrement en ce qui a trait à l'enlèvement du phosphore total et des algues.

Deux types de toiles de 10 et 5 µm ont été étudiées avec un taux de chargement hydraulique de 4.0 à 9.2 m/h et un taux de chargement des MES de 15.7 à 574.1 g-MES/m^2/h. L'évaluation a souligné un taux de chargement maximal de 6.85 m/h pour la toile de 5 µm, comparativement à la toile de 10 µm qui n'as pas démontré de limite quant aux taux de chargement hydrauliques appliqués dans cette étude. La performance de la toile de 10 µm dépendait des opérations des étangs en aval du système, en particulier de l'application du système d'aération. La toile de 10 µm a réalisé un enlèvement des MES qui satisfait aux exigences fédérales canadiennes (<25 mg/L) pour tous les essais lors de la période de non-aération de l'étang final, en amont du *discfilter*. Par contre, la toile de 10 µm était susceptible aux changements des caractéristiques des MES durant l'aération de l'étang final, avec 80% des données de concentration des MES étant non-conformes (>25 mg/L). La toile de 5 µm a démontré une capacité à générer un effluent de haute qualité par rapport aux MES (<10 mg/L) dans toutes les conditions. L'évaluation des avantages secondaires a démontré un enlèvement de phosphore total d'un affluent de 0.3 à 0.8 mg-P/L à un effluent ≤0.3 mg-P/L. De plus, l'utilisation du *discfilter* a maintenu une concentration d'algues/ Chlorophylle α ≤7 µg-Chl.α/L pour un affluent de 4 à 24 µg-Chl.α/L.

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BAF – Biological Aerated Filter

BFS – Blast Furnace Slag Filter

BNR – Biological Nutrient Removal

BOD – Biological Oxygen Demand

cBOD – Carbonaceous Biological Oxygen demand

CAS – Conventional Activated Sludge

Chl. α – Chlorophyll α (Algae Quantification)

CMD – Cubic Meters per Day

COD – Chemical Oxygen Demand

CW – Constructed Wetland

DAF – Dissolved Air Flotation

DN – Denitrification

DO – Dissolved Oxygen

DOC – Dissolved Organic Carbon

EC – Emerging Contaminant

EPA – United States Environmental Protection Agency

EU – European Union

FC – Fecal Coliforms

FBBR – Fixed-Bed Biofilm Reactor

HGL – Hydraulic Grade Line

HRT – Hydraulic Retention Time

HSSF – Horizonal Subsurface Flow (Wetlands)

H_2S – Hydrogen Sulfide

MBBR – Moving-Bed Biofilm Reactor

MF – Micro-filtration

MLD – Million Liters per Day

MPN – Most Probable Number

NIT – Nitrification

Org. N – Organic Nitrogen

Ortho-P – Orthophosphates

Poly – Polymer (coagulation)

PS – Pilot Scale

SAGR – Submerged Attached Growth Reactor

SRT – Solids Retention Time

TAN – Total Ammonia Nitrogen

TKN – Total Kjeldahl Nitrogen

TN – Total Nitrogen

TOC – Total Organic Carbon

TP – Total Phosphorus

TSS – Total Suspended Solids

SS – Suspended Solids

US – United States

u.n.o. – Unless noted otherwise

VF – Vertical Subsurface Flow (Wetlands)

VSS – Volatile Suspended Solids

WSER – Wastewater Systems Effluent Regulations (Canada)

WRRF – Water Resources Recovery Facility

1 Introduction

1.1 Background

1.1.1 Context of wastewater treatment

Municipal wastewater is a common waste product that is generated and treated in municipal wastewater treatment systems. Wastewater in Canada is the generation of 5.9 billion cubic metres of sewage per year, and the servicing of just over 30 million people through major wastewater infrastructure (>100 CMD) (Statistics Canada, 2019).

Wastewater discharge is one of the major contributors to water pollution. Since the contaminants found in municipal wastewater have adverse impacts on the ecology, eutrophication, and water toxicity of the receiving waters, wastewater is treated prior to discharge to mitigate the environmental impact. The treatment of wastewater can effectively remove its principal contaminants including: organic matter, nutrients, solids and other health impacting contaminants such as pathogens (Wentzel et al., 2003; Holeton et al., 2011; Tchobanoglous et al., 2014). The commonly deployed technologies for the treatment of wastewater are lagoon systems (a passive technology); activated sludge systems (a mechanized technology); and other, more advanced mechanized processes.

The Canadian federal wastewater systems effluent regulations (WSER) outline minimum end-of-pipe regulation through a national performance standard, to limit water pollution by effluent from water resource recovery facility (WRRF) effluent and combined sewer overflow. These regulations mandate secondary treatment as mandatory minimum level of treatment for WRRFs. In Canada, 26% of wastewater undergoes primary treatment, while 48% and 24% undergoes secondary and tertiary treatment respectively (Statistics Canada, 2019). The federal criteria imposes thresholds on cBOD, TSS, un-ionised ammonia, and residual chlorine concentrations in wastewater treatment plant effluent, as well as a non-lethality criterion (Oleszkiewicz and Barnard, 2006; Mavinic et al., 2018a; b). In Canada, the US and the EU, the minimum treatment regulations are also becoming increasingly stringent.

1.1.2 Lagoon systems and performance gaps

Lagoons in Canada accounted for 1244 of the 3500 publicly owned WRRFs used for municipal wastewater treatment in 2016, serving 7% of the population. In comparison, there are about 8000 lagoon facilities in the US, and in both countries, lagoons represent about 50% of the publicly owned wastewater treatment facilities, by number. This distribution has notably been stable in Canada and the US since the 1980's (Environmental Protection Agency, 2011; Mavinic et al., 2018c; Statistics Canada, 2018).

In addition to effective removal of a considerable fraction of wastewater contaminants, the main advantage of lagoons is their efficient operational performance due to: minimal operational inputs, low capital investment, infrequent need for sludge removal, and relatively low energy requirements, particularly if the system is designed to operate with gravity flow.

These advantages lead to an overall low cost of treatment (Environmental Protection Agency, 2011). Lagoons present inherent gaps of performance in relation to TSS removal, Nitrogen removal and Phosphorus removal. Due to these gaps in performance, and to the implementation of stricter regulations, the application of this technology may be restricted on the basis of regulation compliance. To upgrade lagoons while maintaining the advantages of these passive wastewater treatment systems, upgrade technologies need to be compatible with lagoons in terms of operational intensity, capital investment, small land footprint and energy costs in order to be deemed compatible and appropriate.

Typically, the treatment performance of lagoon processes demonstrate good treatment capacity for cBOD at low overall and operational and maintenance costs (Environmental Protection Agency, 2011). Lagoons are an effective and efficient technology for the treatment of BOD, and do not have a systemic gap in performance requiring urgent upgrade.

Moreover, nitrification in lagoon systems is achievable in some cases, with removal ranging from 40 to 95% (Crites et al., 2014). The effectiveness of nitrification in lagoons is unreliable in temperate climates, such as Canada and the northern US, because of declining wastewater temperatures during winter. Achieving cold-temperature nitrification has been a research interest for all wastewater processes affected by cold water temperatures (Van Dyke et al., 2003;

Head and Oleszkiewicz, 2004; Hoang et al., 2014; Young et al., 2016). There is a gap of performance for nitrogen removal in lagoons as well as a gap of knowledge on the appropriate technologies to supplement lagoon nitrification and denitrification to achieve nitrogen removal within these systems.

Likewise, solids are a contaminant that is of central concern to the operation of lagoons. The principal factors affecting the solids removal performance of these systems is the complex and dynamic generation of biological solids in the lagoon related to cell growth, algae growth, and other pond detritus material. In lagoons, due to the passive operation of the systems, the understanding of the solids characteristics within these systems is limited. Lagoons are also limited to the use of settling processes for solids removal, which have an added degree of complexity due to hindered settling within the benthic zone, bulking, resuspension, among other mechanisms.

Furthermore, the removal of phosphorus is problematic across all WRRFs, including lagoons. In lagoons specifically, removal is low and typically under 40%, with some reports as low as 15-25% (Environmental Protection Agency, 2011; WEF, 2018). Phosphorus removal regulations are becoming stricter, and there is a gap in performance in lagoons regarding phosphorus removal that is often addressed with the use of coagulation (Environmental Protection Agency, 2011). There is a gap of knowledge on different or improved appropriate technologies to achieve lower phosphorus concentrations in lagoon effluent.

Algae control is also a concern for lagoon WRRFs, since algae is a significant contributor to the solids in lagoon effluents, due to its presence being required for some of the treatment mechanisms within lagoons. Algae also contributes significantly to the effluent of BOD in facultative lagoons, and may contribute up to 90% of the unfiltered cBOD in the effluent (Mara, 2004). Algal solids, their morphology, and their growth dynamics have not been systematically characterised in lagoons, and there is an overall gap of knowledge on their role on the effluent solids characteristics of lagoons (Audrey D. Levine, 1985; Levine et al., 1991; Neis and Tiehm, 1997; Sophonsiri and Morgenroth, 2004; Bawiec et al., 2017; Izdori et al., 2018). Furthermore, the generation of solids in lagoons through algae growth and pond detritus also highlight the need for effluent polishing targeting algal suspended solids (Middlebrooks, 1995; Pearson, 2003; Khorsandi et al., 2014).

Overall, solids generation within lagoons highlights a performance gap in lagoon systems of all configurations. There are few viable alternatives for solids removal as well as literature on the subject, and therefore a gap of knowledge in addressing this issue in existing lagoon systems. The available technologies for lagoons have demonstrated a limited to moderate effectiveness in the solids removal. Additionally, the most effective technologies have demonstrated limited adaptability to lagoon wastewater treatment due to excessive operational intensity, sludge management issues and required footprint.

1.1.3 Lagoon treatment challenges

A principal challenge to wastewater treatment in rural communities is the prevalence of passive wastewater treatment systems subject to non-compliance of wastewater effluent regulations. Furthermore, effluent discharge regulations affecting wastewater treatment facilities are becoming increasingly stringent (Government of Canada, 2016). Lagoons, the principal passive wastewater treatment technology, suffer specifically from inherent performance gaps; and trends in wastewater regulation could restrict the application of this low-cost technology on the basis of regulation compliance. Upgrade technologies to these treatment systems may be required to provide enhanced BOD, nitrogen, phosphorus, and solids removal to ensure compliance with effluent quality targets and regulations.

Meanwhile, mechanized wastewater treatment technologies with the capability to generate effluent that complies with stringent regulations require significant infrastructure and operational expenses compared to passive treatment technologies. Rural communities often do not have the financial resources to support these mechanized technologies and, because of their smaller tax base may not have the financial capacity to support the added operational and maintenance expenses, qualified personnel, and fixed costs associated with such systems. Additionally, these communities typically do not generate the volume of wastewater required to make these investments economically beneficial. This limits the economic viability of mechanized wastewater treatment technologies in rural communities, where the financial investment allocated to wastewater treatment would become an important burden.

A more effective and efficient solution, if achievable, would be to upgrade the existing passive treatment technologies to guarantee compliance with the stringent regulations on wastewater contaminants released. For compatibility with lagoon treatment and its advantages in rural communities, appropriate upgrade technologies should similarly have low operational costs and involvement requirements. Additionally, upgrade technologies should be well adapted for performance in low flow conditions and have small land footprint (Mendoza-Espinosa and Stephenson, 1999; Daigger, 2004; Muga and Mihelcic, 2008; Environmental Protection Agency, 2011; Molinos-Senante et al., 2012; Vera et al., 2013; Remy et al., 2014; WEF, 2018). Therefore, an appropriate and compatible upgrade technology would provide effluent that satisfies stricter regulations without compromising the performance and economic advantages of wastewater lagoons.

Looking specifically at the compliance with suspended solids regulations, passive treatment systems such as lagoons, have been shown to be widely non-compliant with respect to effluent suspended solids concentrations. This non-compliance is typically influenced by changes in the characterization and settling characteristics over time, which affect the removal efficiency of solids in these systems throughout their lifespan and also across periods of solids removal and dredging from the lagoons. Solids are therefore an unpredictable wastewater treatment parameter in lagoons.

1.1.4 Discfilter systems

Microsieves are a physical separation technology developed for the treatment of wastewater and the removal of solids. There have been widespread uses of this technology in Canada, the US and especially the EU with over 300 installations, although there are limited reports in literature on the performance of these systems (Golueke and Oswald, 1965; Al-layla et al., 1974; Harrelson et al., 1982; Grabbe et al., 1998; Bourgeous et al., 2003; Remy et al., 2014). Discfilters specifically have also been installed in a handful of mechanized WRRFs of Canadian municipalities with capacities up to 240 MLD (Veolia Water Technologies, Canada).

Operational advantages of microsieves include the low cost, simplicity of operation, limited maintenance requirements, operational flexibility and adaptability, high hydraulic flexibility, low headloss, small footprint, and low energy requirements. Recent studies on the use of discfilters have employed these systems following secondary mechanized treatment trains, with strict effluent quality targets for solids and phosphorus (Kängsepp et al., 2016; Langer et al., 2017). Applications included solids removal and concurrent phosphorus removal for wastewater reuse and the removal of hard to settle suspended solids in Conventional Activated Sludge (CAS) and Moving-bed Biofilm Reactor (MBBR) effluent polishing. The effective performance of the discfilter technology in addition to its advantages of low footprint, low energy consumption and low operational intensity fulfill the compatibility requirements for lagoon systems and rural wastewater treatment.

Discfilters have yet to be applied to lagoon systems for the removal of effluent suspended solids. Additionally, discfilters have yet to be studied for peripheral removal of phosphorus and algae. There is a specific gap of knowledge on the performance of discfilters, with respect to the removal of solids, phosphorus and algae in lagoons and similarly characterised effluent.

1.2 Study objectives and importance

The objective of this study is to investigate the performance of discfilters as applied to lagoon systems. This study will bridge the performance and knowledge gaps that surround upgrading solids removal performance in lagoons whilst meeting the specific challenges of lagoon and rural wastewater treatment.

The primary objective of this study is the characterization of suspended solids removal using a discfilter. To fulfill this objective, solids removal performance was investigated in response to hydraulic loading, solids loading, and filter cloth without the addition of coagulant or flocculant. The secondary objective of this study is the characterization of peripheral water quality benefits specific to lagoons: the removal of phosphorus and algae. The performance characterization was also investigated in response to hydraulic loading, solids loading, and filter cloth.

This research is seeking to deploy and demonstrate an end-of-line treatment technology for the removal of suspended solids in a lagoon system. This technology, the Hydrotech® discfilter

(Veolia Water Technologies, Sweden), has previously been successfully demonstrated for solids and phosphorus removal applications in mechanized secondary treatment systems, and the successful implementation of this technology to lagoon systems would bridge the gap of knowledge for appropriate and compatible solution for the control of suspended solids and associated peripheral benefits to lagoon wastewater treatment.

Since lagoons represent a large fraction of the wastewater infrastructure, the impact of the stricter regulations has considerable implications for stakeholders involved with wastewater treatment infrastructure. In the case of upgrading lagoon systems, municipalities using these systems stand to gain significant benefits in having an upgrade option that is compatible with the systematic advantages of lagoons.

1.3 Thesis organisation

Chapter 1 highlights the context of the study, followed by research objectives and research contributions relating to this work. Chapter 2 consists of a literature review that provides an overview on the context of wastewater treatment, how it relates to lagoon systems and rural wastewater treatment, as well as the current developments relating to available upgrade technologies for lagoon systems. Chapter 3 presents the manuscript that resulted from this research: *Removal of wastewater lagoon solids using discfiltration*, which is to be published in the Journal of Environmental Engineering (ASCE). Finally, Chapter 4 provides an overview and synthesis of the engineering and design implications as they relate to the implementation of this study's findings.

1.4 Contribution of authors

The research work outlined in this thesis resulted in a scientific manuscript prepared for publication. The contributions of each author with respect to the work is outlined below. This article is formatted for publication in the Journal of Environmental Engineering (ASCE).

<u>Article:</u> G. LeBlond, C. Kinsley, P.M. D'Aoust, S. Vincent, R. Delatolla. *Removal of wastewater lagoon solids using discfiltration.* In preparation for submission for publication.

G. LeBlond: conducted on-site sampling and testing, data analyses and wrote the article.

C. Kinsley: provided technical assistance and supervision of the project.

P. M. D'Aoust: provided technical assistance as well as on-site equipment installation and maintenance, and project guidance.

S. Vincent: provided technical assistance as well as on-site equipment installation and maintenance, and project guidance.

R. Delatolla: supervised the project, directed the study and oversaw the writing of the manuscript.

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2 Literature review

2.1 Municipal wastewater

Municipal wastewater is a common waste product that is generated and treated in municipal wastewater treatment systems in Canada, the United-States (US) and the European Union (EU). Wastewater, in Canada generates 5.9 billion cubic metres of sewage per year, servicing just over 30 million people through major wastewater infrastructure (>100 CMD) (Statistics Canada, 2019).

Wastewater discharge is one of the major contributors to water pollution. Since the contaminants found in municipal wastewater have adverse impacts on ecology, eutrophication, and water toxicity of the receiving waters, wastewater is treated prior to discharge to mitigate the environmental impact on these waters. The treatment of wastewater can effectively remove its principal contaminants, including organic matter, nutrients, solids and other health impacting contaminants including pathogens (Wentzel et al., 2003; Holeton et al., 2011; Tchobanoglous et al., 2014).

In terms of characterisation of these compounds, organic matter is characterised as carbonaceous biological oxygen demand (cBOD) or often as chemical oxygen demand (COD). The nutrient component of wastewater includes nitrogen compounds: total ammonia nitrogen (TAN), nitrite, and nitrate; and phosphorus compounds: as total phosphorous (TP) or ortho-phosphates (Ortho-P). The discharge of organic matter and nutrients has impacts on receiving waters including reduced dissolved oxygen (DO) content, increased eutrophication potential, and toxic effects on the affected ecosystem (Sedlak, 1991; Daigger, 2004; Holeton et al., 2011; Tchobanoglous et al., 2014).

Solids, in particular the fraction characterized as total suspended solids (TSS), have a negative impact on aquatic ecosystems and are therefore a targeted contaminant in Canadian, American and European wastewater effluent regulations. TSS consist of the particulate fraction of wastewater and contains fractions of organic matter, metals, sediment, and can adsorb other contaminants such as pesticides and heavy metals, exacerbating their effects on the environment. TSS can also be a source of particulate phosphorus compounds, which contributes to eutrophication. TSS has other impacts on waterways, decreasing the penetration of light, negatively impacting fish and benthic organisms in waterways, and by acting as a surrogate for the transport of pathogens (Bilotta and Brazier, 2008; Chahal et al., 2016).

Advances in analytical methods for characterizing wastewater have expanded the range of compounds of concern in wastewater to include emerging contaminants (ECs). These contaminants are being characterized for their impact on the environment, their behaviour, and removal in wastewater treatment systems (Servos et al., 2005; Petrie et al., 2014).

2.2 Regulations

2.2.1 Canadian regulations

In Canada, the federal wastewater systems effluent regulations (WSER) outline minimum end-of-pipe regulation for Canada through a national performance standard, to limit water pollution by wastewater from wastewater treatment plant effluent and other sources. The federal criteria impose thresholds on cBOD, TSS, un-ionised ammonia, and residual chlorine concentrations in wastewater treatment plant effluent, as well as a non-lethality criterion (Oleszkiewicz and Barnard, 2006; Mavinic et al., 2018a; b).

Provinces may apply for equivalency agreements to permit them to impose equal or more stringent regulations compared to the federal legislation and they can be granted authority on wastewater regulation and monitoring, in accordance with WSER. A comparative table of regulations in Canada is provided in Table 2-1.

With respect to nutrient removal, sensitivity of receiving waters is the most often considered aspect in determining the level of treatment required. The disparities in levels of treatment is notable when comparing practices in eastern Canada and western Canada. Eastern Canada generally has less restrictive standards, in some cases focusing on regulating watersheds deemed “at-risk” as is the case in Ontario, Canada. Meanwhile in western Canada, advanced nutrient removal technologies have been implemented such as biological nutrient removal (BNR) and stricter regulations have been imposed on the discharge of total nitrogen (TN) and TP (Oleszkiewicz and Barnard, 2006; Mavinic et al., 2018a; b). Concerning ECs, regulations on the required level of treatment of these compounds are in their infancy and most jurisdictions are at the stage of developing guidelines for the treatment of these compounds (Mavinic et al., 2018b).

Table 2-1. Canadian WSER and provincial regulations; adapted from (Mavinic et al., 2018b)

		Legislating body						
		Canada	BC	Alberta	Saskacthewan	Manitoba	Ontario	Quebec
Parameter	$cBOD_5$	<25 mg/L	<45 /<10 mg/L*	<25 / <20 mg/L*	<25 mg/L*	<25 mg/L*	<25 mg/L *	<25 mg/L
	TSS	<25 mg/L	<45 /<10 mg/L*	<25 / <20 mg/L*	<25 mg/L	<25 mg/L	<25 mg/L *	<25 mg/L
	TAN / Nitrification	<1.25 mg - N/L*	-	site-specific*	-	<1.25 mg/L or **	Regulated**	-
	TN / Denitrification	-	-	-	-	<15 mg/L	-	-
	TP	-	<1 mg - P/L & Ortho-P <= 0.5 mg/L **	<1 mg - P/L*	-**	<1 mg - P/L	<0.5-1 mg/L up to <0.1 mg/L for sensitive waters	
	pH		6-9					6-9.5
Regulation type	End-of-pipe							
	Site specific							
Notes	*	Un-ionized ammonia	Based on dilution ratio	>20 000 people	BOD_5 <30 mg/L	BOD_5 <25 mg/L (incl. nitrification)	Technology dependent	
	**	-	Not applicable to marine waters	-	Phosphorus recovery programs	Site specific	Every plant is site specific for all contaminants	

2.2.2 US and EU regulations

In the US, the regulation framework is similar to the federal-provincial system in Canada. The US environmental protection agency (EPA) mandates a secondary treatment effluent criterion, although states may define the effluent limits, which are often more relaxed compared to EPA standards. Regulatory bodies in the United-States have incorporated more elaborate methods beyond technology-based limits of treatment by implementing water quality based limits that include: watershed-specific pollutant plans, maximum yearly discharge average for water resource recovery facilities (WRRFs) and incorporating contaminant removal credit trading programs (Oleszkiewicz and Barnard, 2006; WEF, 2011; Mavinic et al., 2018b).

The EU also follows a federation-state format of regulations, but like in Canada, the EU regulations are a minimum standard and member countries may impose stricter regulations as appropriate. Overall, EU regulations are stricter than Canadian regulations, mandating nutrient removal through nitrogen and phosphorus effluent discharge limits, and also mandating minimum percentages of removal. Conversely, EU regulations are not as strict towards suspended solids as compared to the practice in US and Canada. The level of treatment mandated is either tertiary or secondary based on the population served. Nutrient removal in the EU also uses site-specific criteria depending on the eutrophication potential of receiving waters. Concerning emerging contaminants, guidelines on the treatment of these compounds are still being developed, and only Switzerland has implemented regulation targeting ECs specifically (EPA, n.d.; Oleszkiewicz and Barnard, 2006; Environmental Protection Agency, 2011; Mavinic et al., 2018b). For comparison, sample regulation thresholds from the US and the EU are shown in Table 2-2.

Table 2-2. US, EU and EU country regulations

		Legislating body							
		US EPA	EU	Germany	Poland	Switzerland	Austria	Netherlands	Denmark
Parameter	$CBOD_5$	<25 mg/L 85% removal	<25 mg/L, 70-90% removal	<15 mg/L	-	<15 mg/L	<15 mg/L	<20 mg/L	-
	COD	-	<125 mg/L	<75 mg/L	-	<60/<45 mg/L 80-85% removal	<75 mg/L	-	-
	TSS	<30 mg/L 85% removal	<35 mg/L	<30 mg/L	<20 mg/L	-	<35 mg/L	<30 mg/L	-
	TAN / Nitrification	-	-	<10 mg/L	-	<2 mg/L 90% removal	<5 mg/L	-	-
	TN / Denitrification	-	15/10 mg/L, 70-80% removal	<13 mg/L	-	Site specific*	70% removal	-	<8 mg/L
	TP	2/1 mg/L 80% removal	2/1 mg/L 80% removal	-	-	<0.8 mg/L 80% removal	-	-	<1.5 mg/L
	pH	6.0-9.0	-	-	-	-	-	-	-
Notes	*	30 day average	Population threshold on regulations	TOC regulated		Additional req's : DOC <10 mg/L, 80% removal of trace organics			

Sources: (EPA, n.d.; Oleszkiewicz and Barnard, 2006; Environmental Protection Agency, 2011; Mavinic et al., 2018b)

2.3 Commonly employed technologies

In Canada, 26% of wastewater undergoes primary treatment, while 48% and 24% undergoes secondary and tertiary treatment respectively (Statistics Canada, 2019). Commonly deployed technologies for the treatment of wastewater are lagoon systems (passive); activated sludge systems (mechanized); and other, more advanced mechanized processes. Considerable differences exist between passive and mechanized treatment technologies, specifically in their associated land use, pumping requirement, accepted flowrates, wastewater strength, solids management and operational intensity. The selection of treatment technologies is performed through a process of feasibility analyses that consider treatment performance and overall system cost, with availability of capital and utilities playing a role as well.

2.3.1 Conventional technologies

2.3.1.1 Conventional activated sludge

Conventional activated sludge (CAS) is the standard mechanized, biological treatment technology. CAS works by decoupling the hydraulic retention time (HRT) and solids retention time (SRT), thereby improving biological treatment through the reuse of biomass. CAS systems work by aerating the mixed liquor and uses a fraction of the subsequently settled biological solids to provide the necessary active biomass for the oxidation of cBOD, and occasionally, the oxidation of TAN (Tchobanoglous et al., 2014).

Mechanized systems, like CAS, are complex systems requiring a considerable number of inputs in order to operate; but are very effective for treating wastewater at lower footprints than passive systems. Mechanized WRRFs consist of treatment trains containing multiple unit processes supporting the principal CAS process for effective wastewater treatment and efficient system performance. These unit processes may include: screening, grit removal, primary settling, biological treatment, secondary settling, disinfection and often include sludge management processes as well. Additional disadvantages of this technology include the management of generated sludge and solids streams required by these systems (Tchobanoglous et al., 2014).

2.3.1.2 Lagoons

Lagoons are the conventional passive treatment technology, employing very long detention times to enable the degradation of contaminants using algae or aerators to provide the necessary DO to sustain the biological processes. Lagoons are effective at removing BOD, wastewater solids and are able to perform nitrification seasonally. These technologies are more suitable for lower flows and volumes, and require a correspondingly large area per BOD loading (Pearson, 2003; Van Dyke et al., 2003; Environmental Protection Agency, 2011; Crites et al., 2014; Mavinic et al., 2018a; WEF, 2018).

The main advantage of this technology is the passive nature of treatment that does not require significant operational intensity for the maintenance of the process or the management of biosolids. Although passive technologies reduce the operational intensity, control of these systems is limited since the process is affected by seasonality and by ambient temperatures. Therefore, a variety of system configurations are used to design systems with multiple cells to ensure a robust system, capable of meeting target treatment objectives. The models of this process used for design are not necessarily mechanistic in nature and are not always representative of system performance (Ho et al., 2017).

2.3.2 Advanced technologies

Developments in wastewater treatment technologies have brought forward improvements on CAS-like processes such as extended aeration and biological nutrient removal, as well as the advent of attached growth biological treatment through biological aerated filters (BAFs) and moving-bed biofilm reactors (MBBRs).

2.3.2.1 Extended aeration

The extended aeration process is an activated sludge system based on extending the HRT of CAS to achieve complete nitrification and performance of conventional primary and secondary treatment within one tank. This system may have potential solids separation issues due to the operating conditions promoting pin floc, affecting the solids and sludge characteristics (McCarty and Brodersen, 1962; Richard, 2003).

2.3.2.2 Biological nutrient removal

WRRFs using BNR are mechanized treatment plants that utilize intensive processes to achieve complete nutrient removal. This is typically achieved using various suspended growth supplementing processes such as biomass enhancement, nitrate recirculation, enhanced biological and/or chemical phosphorus removal, and other add-on processes applicable to CAS-like processes. The operation of these plants is complex and energy intensive (Oleszkiewicz and Barnard, 2006; Oleszkiewicz et al., 2015).

2.3.2.3 Moving-bed biofilm reactors

MBBRs are an attached growth treatment technology with a wide range of operational capabilities, small footprint and wide-ranging applications. This technology is emerging in Canada and the US but is well-established in Europe. It is recognised for compactness, versatility and simplicity as well as performance specific advantages such as higher volumetric reaction rates and capacity as well as increased biofilm-related process stability and low effluent solids output (Morgan-Sagastume, 2018). The key advantage of this technology are enhanced volumetric efficiency and specific process dynamic of attached growth, and less sludge production

2.3.2.4 Biological aerated filters

BAFs are another type of attached growth treatment technology. This technology is well adapted for larger flows, and has improved performance relative to CAS, allowing for energy savings at larger scales because of efficiency gains (Mendoza-Espinosa and Stephenson, 1999; Payraudeau et al., 2001; Delatolla et al., 2010).

2.4 Lagoons

Lagoons in Canada comprise of about 1244 of the 3500 publicly owned WRRFs used for municipal wastewater treatment in 2016, serving 7% of the population. In comparison, there are about 8000 lagoon facilities in the US, and in both jurisdictions, lagoons consist of about 50% of the publicly owned wastewater treatment facilities, by number. Notably this distribution has been stable in Canada since the 1980’s (Environmental Protection Agency, 2011; Mavinic et al., 2018c; Statistics Canada, 2018).

2.4.1 Facultative lagoons

Facultative lagoons are widely used in North America for the treatment of municipal wastewater. The most notable advantages of these systems are the reduced operational requirements coupled with effective removal of settleable solids; BOD_5; pathogens; and, less reliably, TAN (Pearson, 2003; Van Dyke et al., 2003; Environmental Protection Agency, 2011; Crites et al., 2014; Mavinic et al., 2018a; WEF, 2018).

In these systems, 80% of the DO is supplied through algal photosynthesis, with mass transfer from the water surface being another source of DO. The supply of DO limits the oxidation capacity per unit area and therefore BOD loading rate. Facultative lagoons therefore require relatively large surface areas, require long detention times, and are shallow to allow for maximum oxygen production through algal photosynthesis (Mara, 2003; Pearson, 2003).

The technology benefits from effective removal of a considerable fraction of wastewater contaminants as well as low operational intensity due to minimal operational inputs, low capital investment, infrequent need for sludge removal, and relatively small energy requirements, particularly if the system is designed to operate with gravity flow. These advantages lead to an overall low cost of treatment (Environmental Protection Agency, 2011).

2.4.2 Aerated lagoons

As an alternative to facultative lagoons, aerated lagoons are another frequently used lagoon configuration. In areas where there are constraints on suitable location, lagoons may be designed with lower HRTs by supplying DO to the water column with mechanical aerators and agitators, allowing aerated lagoons to be smaller in size than facultative configurations. This also allows the systems to be smaller for a same contaminant (BOD, N) and flowrate.

Aerated lagoons have drawbacks such as being operationally more complex than facultative lagoons, and having consequently higher operating costs. Aerated lagoons are also more prone to having excess TSS in the water column, due to resuspension by the aeration process (Environmental Protection Agency, 2011).

Overall since lagoons are passive systems that are exposed to the elements, they are susceptible to seasonal variations in performance. They are one of the prevalent centralized wastewater treatment technologies in rural communities.

2.4.3 cBOD removal

CBOD removal in wastewater systems includes the removal of its particulate factions through physical separation or settling and the treatment of its soluble fractions through biological processes. Transfer between these phases can occur through solubilisation of the particulate phase of cBOD. Soluble BOD constituents are treated principally by heterotrophic aerobic micro-organisms that oxidise and assimilate the soluble constituents through their metabolism, which, by increasing the bacterial mass, are then separated in the form of settled biosolids. The biological process is supported through the providing DO, soluble biodegradable fractions of BOD (from wastewater), as well as nutrients (Tchobanoglous et al., 2014).

Overall, facultative and aerated lagoon processes show a good treatment capacity of cBOD at low overall and operational and maintenance costs (Environmental Protection Agency, 2011).

2.4.4 Nitrogen removal

Nitrogen in the influent of lagoons is principally under the form of ammonia-nitrogen, characterised as TAN. The principal conventional removal pathways for nitrogen removal are nitrification and denitrification.

Nitrification in wastewater systems is a biologically-mediated process, transforming TAN to nitrate and nitrite. The micro-organisms responsible for the process are autotrophic aerobes. Because of their lower metabolic efficiency and lower specific growth rate relative to heterotrophic aerobes responsible for BOD removal, competitive inhibition is an important mechanism affecting this process. For nitrification processes to occur, BOD must be limited and pH, alkalinity, and temperature must be within the acceptable range (Sedlak, 1991; Tchobanoglous et al., 2014).

Temperature has a significant impact on nitrification, where cold temperatures below 15°C inhibit the process and temperatures below 4°C stunt the activity of the bacteria altogether. Achieving low-temperature nitrification has been a research interest for temperate climates to better achieve nitrification in all wastewater processes (Van Dyke et al., 2003; Head and Oleszkiewicz, 2004; Hoang et al., 2014; Young et al., 2016).

Nitrification in lagoon systems is achievable in some cases, removal ranging from 40 to 95% removal (Crites et al., 2014). The effectiveness of nitrification in all lagoons is unreliable in temperate climates, such as Canada and the northern US, because of declining wastewater temperature during winter. Meanwhile, facultative lagoons may experience additional difficulties with nitrification from the seasonal increase of apparent carbon loading (and subsequent increase in CBOD:TKN ratio) due to the loss of DO production capacity and therefore BOD treatment. This seasonal variation is also exacerbated due to the breakdown and decomposition of organic matter and macrophytes. Furthermore, cold temperatures will cause a reduction in the oxygen producing macrophytes and algae, and the onset of ice cover on lagoons will inhibit wind-induced reaeration of the water column (Chen et al., 2019). These changes may further cause anaerobic conditions to occur in the lagoon, permitting the generation of Hydrogen Sulfide (H_2S) which is toxic to nitrifiers and DO producing algae (Mara, 2004). Studies have identified the values of a CBOD:TKN ratio of 1:1 or less and a soluble BOD concentration ≤20 mg/L as the threshold at which nitrification will occur. Conditions outside this range will prolong the period during which nitrification is absent, due to nitrifying bacteria being outcompeted, reducing the available period in which nitrification occurs in facultative lagoons (Hurse and Connor, 1999; Van Dyke et al., 2003; Daigger, 2004; Picot et al., 2009; Environmental Protection Agency, 2011).

Denitrification is the biologically mediated transformation of nitrate to elemental nitrogen, nitrogen oxide and nitrogen dioxide. Denitrification is a heterotrophic-facultative process and only occurs in areas where DO is depleted, in the presence of nitrate as terminal electron acceptor and in the presence of a carbon source. In facultative lagoons, due to the diurnal cycle of algal oxygen production, the changing conditions allow denitrification to occur in the different stratified zones of the water column (Mara, 2004). Conversely, in aerated lagoons these conditions do not occur, limiting the extent of denitrification except in the benthic zone where dissolved oxygen is depleted.

Compared to nitrification, denitrification is not as sensitive to temperature impacts on micro-organisms. The onset of denitrification in facultative lagoons has been observed to follow closely the onset of nitrification provided enough nitrifying biomass has accumulated to allow for the variation of DO during the diurnal cycle and the production of nitrates for denitrification (Gschlößl et al., 1998; Hurse and Connor, 1999; Archer and Donaldson, 2003; Cameron et al., 2003; Picot et al., 2009; Crites et al., 2014; Anderson et al., 2015).

Due to the susceptibility of nitrification being stymied in conventional lagoon systems, and since nitrification is required to achieve denitrification; improving nitrification within lagoon systems is the main challenge to ensure compliance with stricter regulations targeting TAN and TN removal. There is a gap of performance for nitrogen removal in lagoons as well as a gap of knowledge on the appropriate technologies to supplement lagoon nitrification and denitrification in order to achieve nitrogen removal from these systems.

2.4.5 Phosphorus removal

The removal of phosphorus is problematic across all WRRFs. In lagoons, phosphorus initially gets stored in the benthic zone through storage in slowly decaying organic matter, but is then released through anaerobic processes into the water column (Levine et al., 1985; Maynard et al., 1999). The level of phosphorus removal in lagoons is generally low, typically under 40% (WEF, 2018), with reported ranges of removal as low as 15-25% (Environmental Protection Agency, 2011).

Phosphorus compounds readily precipitate with the use of coagulating salts and polymers. The use of these compounds is widespread in lagoon system to control phosphorus levels, is considered to be the only effective phosphorus removal process (Environmental Protection Agency, 2011). Notably, alum addition can improve removal rates from 37% up to 81% in the removal of soluble Ortho-P (Crites et al., 2014).

Phosphorus removal regulations are becoming stricter, and there is a gap in performance in lagoons regarding phosphorus removal that is often addressed with the use of coagulation (Environmental Protection Agency, 2011). There is a gap of knowledge regarding the different or improved appropriate technologies to achieve lower phosphorus concentrations in lagoon effluents.

2.4.6 Pathogen removal and emerging contaminant fate

Pathogens in wastewater are a recognised hazard for human health and are therefore a target for removal by WRRFs. Conventionally, WRRFs remove pathogens through chlorination-based disinfection, most often used in mechanized treatment plants (Curtis, 2003).

In facultative lagoons and maturation ponds, the lower pathogenicity of the effluent is attributable to the long detention time favouring die-off and predation, and the pH rise due to algal activity (Pearson, 2003). Conversely, aerated lagoons are not as effective at removing pathogens due to the shorter retention times (Archer and Donaldson, 2003; Curtis, 2003; Davies-Colley et al., 2003; Mara, 2003; Pearson, 2003; Environmental Protection Agency, 2011; Verbyla and Mihelcic, 2015; Matamoros et al., 2016; WEF, 2018).

Facultative lagoons, and to a lesser extent, aerated lagoons have been observed to provide removal of emerging contaminants and micropollutants, to a higher degree than activated sludge systems or wetlands (Servos et al., 2005; Anderson et al., 2015; Matamoros et al., 2016).

2.4.7 Solids removal

Solids are a contaminant that is of central concern to the operation of lagoons. In mechanical WRRFs, solids are removed principally through settling mechanisms. Mechanical separation processes are also used and include membranes, microsieves, sand filters, and filter presses.

Characterisation of solids in wastewater is the cornerstone in the design of separation processes. For raw wastewater, and wastewater following primary and secondary mechanized treatment, the characteristics of the solids are generally well-known (Levine et al., 1985) and systems are mechanistically designed to remove the solids to satisfy effluent requirements. In lagoons, the understanding of the characteristics of solids within these systems is limited, since lagoons operate on a passive basis and are designed empirically rather than mechanistically for solids removal (Ho et al., 2017). Lagoon systems are also limited to the use of settling processes, which have an added degree of complexity due to hindered settling, bulking, resuspension, among other mechanisms. Influent raw wastewater solids of lagoon systems are treated and settled out (WEF, 2018). The principal issue affecting the solids removal performance of these systems is the generation of biological solids in the lagoon, related to cell growth, algae growth and other pond detritus material. Algae is a significant contributor to the solids in lagoon effluents, since it is required for some of the treatment mechanisms within lagoons. Algae also contributes significantly to the effluent of BOD in facultative lagoons and may contribute up to 90% of the unfiltered cBOD in the effluent. TSS performance of facultative lagoons is based on the level of algae separation, the design of the effluent structure, and the use of maturation ponds (Mara, 2004; Environmental Protection Agency, 2011). Algal solids, their morphology and growth dynamics have not been systematically characterised in lagoons and there is an overall gap of knowledge on the solids characteristics of lagoons (Levine at al., 1985; Levine et al., 1991; Neis and Tiehm, 1997; Sophonsiri and Morgenroth, 2004; Bawiec et al., 2017; Izdori et al., 2018).

Algae populations in all lagoon systems are dynamic and the speciation of algae is dependent on the concentration of BOD (Pearson, 2003). This impacts the removal of algae as studies that have targeted the removal of algae in lagoons have found that the speciation of algae had significant impacts on the performance of DAF systems on algae removal (Buisine and Oemcke, 2001). Quantitively, based on the chlorophyll α pigment concentrations for algae, research has observed that 100 µg/L of Chl. α corresponds to 2.6 mg/L of BOD and 8.5mg/L COD (Gschlößl et al., 1998). Other rough estimates have put these values at 1.1 mg BOD/L and 4.2 mg TSS/L per 100 µg/L of Chl. α (Hurse and Connor, 1999; Mara, 2003; Pearson, 2003).

Solids generation within lagoons highlights a performance gap in lagoon systems of all configurations, with performance varying between lagoon configurations. There are few viable alternatives for solids removal and therefore a gap of knowledge in addressing this issue in lagoon systems.

2.4.8 Performance and knowledge gaps

Overall, lagoons are an effective technology for the removal of BOD and pathogens, and have advantages of low operational intensity, low capital costs and low energy requirements over other treatment technologies. With the implementation of stricter regulations, gaps in performance are of an increasing concern for WRRFs. For lagoons specifically, there is a lack of detailed knowledge with respect to solids removal. Subsequent gaps of knowledge exist within the means to achieve sustainable, reliable nitrogen removal; the removal of phosphorus; and finally, the characterisation, generation, and removal of algal solids.

2.5 Upgrading lagoons

2.5.1 Technologies for the removal of BOD

Lagoons as a technology effectively remove BOD from wastewater. Upgrading performance of lagoons for this specific contaminant could increase the existing systems' capacity with less impact on land use. A table summarizing the principal studies on upgrade technologies for the removal of BOD in lagoons is found in Table 2-3.

Physical expansions and upgrades for lagoons have previously been somewhat successful in enhancing the removal of BOD through the use of aerators, adding facultative lagoon cells, lagoon surface area or remediating hydraulic inefficiencies within individual cells. Results have shown some decreases in effluent BOD levels and some improvement in consistency of the effluent quality. The reported case results within these studies would not be able to meet effluent regulations presented in the previous chapters (Archer and Donaldson, 2003; Picot et al., 2005; Abdel-Shafy et al., 2011).

The removal of BOD through attached growth systems (MBBR, BAF, Fixed-bed Biofilm Reactors (FBBR)) has been studied at length in laboratory settings as well as in mechanized treatment plants and lagoon systems. They achieved effective removal of BOD throughout. Most attached growth systems have been designed for use as a unit process outside of the lagoon systems. Others have been developed as an attached growth system for incorporation in the lagoon systems itself, the advantage being a simple retrofit to existing lagoon systems (Boutet et al., 2018). BAF systems are able to reach similar removal efficiencies as MBBRs and FBBRs, but are disadvantaged at lower flows, since the backwashing requirements of this technology become overbearing (Mendoza-Espinosa and Stephenson, 1999; Schlegel and Koeser, 2007; Leyva-Díaz et al., 2015; Siciliano and De Rosa, 2016; Boutet et al., 2018).

Constructed wetlands have been studied for lagoon effluent polishing, using external cells or by adapting a section of the lagoon cell with plants used in wetland systems. These systems showed some improvement in BOD removals for free surface wetlands, while in some cases the presence of algae in the effluent caused production of BOD in a horizontal sub-surface flow (HSSF) system

(Orth and Sapkota, 1988; Zachritz and Malone, 1993; Gschlößl et al., 1998; Cameron et al., 2003; Rugaika et al., 2019).

Trickling filters can also be used for the polishing of lagoon effluent, achieving good COD/BOD removal rates and effluent concentrations satisfactory to regulations. Some studies have also reported unsatisfactory results and that the performance of trickling filters was not reflective of design formulas for the removal of BOD (Mara et al., 2001; Archer and O'Brien, 2005; Short et al., 2007; Kaya et al., 2007; Avsar et al., 2008).

Rotating biological contactors have also been used and have had comparable efficiencies to constructed wetlands and lagoons, but showcased lower costs compared to activated sludge, and lower footprint compared to trickling filters (Hassard et al., 2015; Matamoros et al., 2016).

Compatible upgrade technologies may be required for lagoon systems to improve the treatment performance of lagoon systems as loading of existing lagoons increases. Lagoons are an effective and efficient technology for the treatment of BOD, and do not have a systemic gap in performance requiring urgent needs to upgrade.

Table 2-3. Summary of lagoon upgrade technologies for BOD removal

BOD Removal										
Technology : Target Contaminant	**Scale**	**COD / BOD**	**Influent Concentration** (mg/L)	**Effluent Concentration** (mg/L)	**Removal Efficiency**	**Loading Rate - Surface Area** ($gX/m^2/d$)	**Loading Rate – Volumetric** ($gX/m^3/d$)	**Removal Rate – Volumetric** ($gX/m^3/d$)	**Hydraulic Loading**	**Source**
Discfilter : TP, TSS	Pilot post mechanized WWTP	BOD	30-50	-	20-30%	-	-	-	-	Langer et al, 2017
MBBR : COD	Lab scale pilot	COD	98-505	50	80%	7.5	-	-	-	Sicilliano and De Rosa, 2016
					90%, peak rate	12.5				
MBBR : NIT, TN	Pilot at WRRF	COD	223.1	42.6	80.91%	-	-	-	-	Leyva-Diaz et al., 2015
		BOD	112	6.87	93.87%					
Bionest FBBR : BOD + NIT	Pilot at aerated lagoon	COD	458	100	44%-78%	4.3	-	-	-	Boutet et al., 2018
			458	160		8.8				
			458	255		22.5				
		BOD	155	-	66%-91%	1.5				
						3				
						7.6				
Submerged FBBR : COD, NIT, DN and TP	Full scale as mechanized treatment	COD	100-900	30-50	-	6-12	-	-	-	Schlegel and Koesser, 2007
BAF : COD, BOD	Review	BOD	-	-	90%	-	8000-10000	-	-	Mendosa-Espinosa, 1999
		COD			93%		1500			
		BOD @ Partial Nitrification			-		Up to 4100			

BOD Removal										
Technology : Target Contaminant	**Scale**	**COD / BOD**	**Influent Concentration** (mg/L)	**Effluent Concentration** (mg/L)	**Removal Efficiency**	**Loading Rate - Surface Area** ($gX/m^2/d$)	**Loading Rate – Volumetric** ($gX/m^3/d$)	**Removal Rate – Volumetric** ($gX/m^3/d$)	**Hydraulic Loading**	**Source**
CW - HSSF : BOD	Pilot	BOD	80	15	81.30%	-	-	-	-	Rugaika et al., 2019
CW : COD,TSS, NIT, DN	Pilot at secondary lagoons	COD	122.5	48.8	58.90%	-	-	-	-	Anderson et al., 2015
CW for Lagoon Retrofit : TSS, COD, algae	Full scale case studies	COD	93	74	20.40%	-	-	-	-	Gschlossl et al., 1998
		COD	120	96	20%					
CW	Pilot	BOD	-	-	32%	-	3-52	-	-	Short et al., 2007
Lagoon					20%					
TF					67%					
TF : COD	Pilot	COD	300-700	-	80-83%	-	-	-	-	Avsar et al., 2008
Trickling Filter : COD, Chl. A	Lab scale	COD	150	25.2	83.2%	-	-	-	0.5	Kaya et al, 2007
				50	66.7%				2	
				50	66.7%				4	
TF and Lagoon Expansion : N, BOD, TSS	Full scale case studies	BOD	Prior	Upgrade	-	-	-	-	-	Archer et al., 2005
			31	24						

BOD Removal										
Technology : Target Contaminant	**Scale**	**COD / BOD**	**Influent Concentration** (mg/L)	**Effluent Concentration** (mg/L)	**Removal Efficiency**	**Loading Rate - Surface Area** ($gX/m^2/d$)	**Loading Rate – Volumetric** ($gX/m^3/d$)	**Removal Rate – Volumetric** ($gX/m^3/d$)	**Hydraulic Loading**	**Source**
Extended aeration lagoon : NIT, COD, TSS	Upgrade of existing lagoon	BOD	606.5	87.9	66.6 to 96.5%	-	-	10 000 winter temp.	-	Abdel-Shafy et al., 2011
		COD	1308.1	277.1	74.2 to 87.8%			23 000 summer temp.		
Lagoon Expansion : TN, BOD, TSS, TP, FC	Full scale	Case 1				-	-	-	-	Picot et al., 2005
		COD	541	216	60%					
		BOD	172	58	66%					
		Case 2								
		COD	645	179	72%					
		BOD	405	50	88%					
Lagoon Retrofit : BOD,TSS NIT, FC	Full scale	Case 1 (BOD)	Existing	Upgrade	-	-	-	-	-	Archer and Donaldson, 2003
			37	30						
		Case 2 (BOD)	Existing	Upgrade						
			40 [19-78]	24 [18-32]						

2.5.2 Technologies for the removal of nitrogen

2.5.2.1 Nitrification

Nitrification performance is unreliable in lagoon systems, and therefore retrofit technologies need to address both challenges in lagoon upgrades. A considerable research effort has been conducted to provide a solution for the removal of TAN at cold temperatures. These developments have been useful for lagoon systems since passive wastewater systems are more dependent on environmental conditions compared to mechanized treatment options. A table summarizing the principal studies on upgrade technologies for nitrification performance in lagoons is found in Table 2-4.

Expansions or configuration modifications using lagoon technologies have been able to provide improved summer nitrification. These improvements have not been able to reduce TAN to levels acceptable by current regulations, and have not been targeted for the improvement of cold temperature nitrification (Archer and Donaldson, 2003; Picot et al., 2005, 2009; Abdel-Shafy et al., 2011).

Attached growth systems have been the principal breakthrough in achieving cold-temperature nitrification, due to biofilm-related behaviours at cold-temperatures. The effectiveness of this technology has been widely demonstrated in literature, with attached growth systems in multiple configurations including MBBR and BAF (Cecen, 1996; Mendoza-Espinosa and Stephenson, 1999; Rusten et al., 2000; Payraudeau et al., 2001; Houweling et al., 2005, 2007; Schlegel and Koeser, 2007; Choi et al., 2008; Delatolla et al., 2010; Hoang et al., 2014; Leyva-Díaz et al., 2015; Young et al., 2016, 2017b; a; Boutet et al., 2018).

Wetlands can also be used as an upgrade technology and provide effective TAN removal, with vertical flow wetlands being the most effective, although this performance does not translate to cold-temperature nitrification. The addition of wetlands following facultative lagoons was found to improve summertime nitrification in temperate climates. Wetlands are passive technologies and have a footprint similar to lagoons, which is considerably larger than end-of-line attached growth systems, which would limit the benefit of wetlands over attached growth systems. (Reed et al., 1995; Cameron et al., 2003; Archer and O'Brien, 2005; Vymazal, 2007; Anderson et al., 2015; Butterworth et al., 2016).

Trickling filters have been used to upgrade effluent polishing and TAN removal in lagoons. Trickling filters allowed for a reduction of mean nitrogen levels and a more consistent effluent quality, although some authors report conflicting observations in performance comparatively to wetlands and with respect to the nitrification rates observed (Archer and O'Brien, 2005; Short et al., 2007; Avsar et al., 2008).

Rotating biological contactors have been able to achieve nitrification at similar rates to MBBR attached growth systems, and have a benefit in treating high strength, TAN-rich waste (i.e. landfill leachate). Research has not been performed on cold-temperature nitrification in these systems (Tchobanoglous et al., 2014; Hassard et al., 2015).

Table 2-4. Summary of lagoon upgrade technologies for nitrification

Nitrification										
Technology : Target Contaminant	**Configuration**	**Influent Conc.** (mg/L)	**Effluent Conc.** (mg/L)	**Removal Efficiency**	**Loading Rate - Surface Area** ($gX/m^2/d$)	**Loading Rate - Volumetric** ($gX/m^3/d$)	**Removal Rate - Surface area** ($gX/m^2/d$)	**Removal Rate - Volumetric** ($gX/m^3/d$)	**Comment**	**Source**
MBBR : NIT	-	22	-	72.5-74.5%	-	-	-	-	Startup	Young et al., 2017
		22	1	96%					Ammonia limit.	
MBBR : NIT	-	22.7	-	-	2.36	-	2		20°C	Young et al., 2017
					0.13		0.09		1°C	
					0.51		0.32		1°C	
					1.25		0.35		Zero-order, 1°C	
MBBR : COD	-	-	-	12%	0.36 (TN)	-	-	-	-	Sicilliano and De Rosa, 2016
MBBR : NIT	-	-	-	-	-	-	-	14.8	1°C	Hoang et al., 2014
								82.4	20°C	
MBBR, BAF : NIT	Biostyr	-	-	-	-	-	-	160-220	-	Delatolla et al., 2010
	Biostyr PS							180	dropped from 260 with temp.	
	MBBR PS							140	dropped from 210 with temp.	
MBBR -post secondary treatment : NIT	-	-	-	-	-	-	-	65	-	Rusten et al., 2000
								68		
								79		
Bionest FBBR : BOD + NIT	NIT	-	-	100%	>0.6	-	-	-	>9.7°C	Boutet et al., 2018
	BOD+NIT	26	26	-	1.3	-	0.06	-	0.4°C	
	BOD+NIT	26	10	-	0.3	-	0.15	-	0.4°C	
	BOD+NIT	26	20	-	0.6	-	-	-	0.4°C	
	BOD+NIT	-	-	-	-	-	>1.5	-	At >5 g CBOD5/m^2/d	
	Temp. Effect	-	-	93%-62%	-	-	-	-	1.9-0.4 °C	

Nitrification										
Technology : Target Contaminant	**Configuration**	**Influent Conc.** (mg/L)	**Effluent Conc.** (mg/L)	**Removal Efficiency**	**Loading Rate - Surface Area** (gX/m^2/d)	**Loading Rate - Volumetric** (gX/m^3/d)	**Removal Rate - Surface area** (gX/m^2/d)	**Removal Rate - Volumetric** (gX/m^3/d)	**Comment**	**Source**
FBBR : NIT	-	-	-	-	-	-	0.3	-	-	Choi et al., 2008
SAGR : NIT	-	-	-	94%	0.007 - 0.025	-	-	-	Overall	Mattson et al., 2018
		19.7	0	97%					"Cold weather"	
Submerged FBBR : COD, NIT, DN, TP	-	20-80 (TKN)	0-10 (TKN)	-	-	-	-	-	Complete nitrification at TKN<2g/m^2/d	Schlegel and Koesser, 2007
		20-80 (TN)	10-25 (TN)	-					40-50% of Tkn removal by periodic aeration	
									Full nitrification at <8 gCOD/m^2/d	
Submerged biofilm reactor : NIT	-	-	-	-	-	77-687	0.66	30	-	Cecen, 1996
							5.94	270		
							8.8	400		
BAF : NIT	-	-	-	-	-	-	-	1000	Partial NIT.	Mendosa-espinosa et al., 1999
BAF : NIT	-	-	1	-	100 - 700	100 - 700	-	-	-	Payraudeau et al., 2001
			1			840			peak load:1mg/L	
			5			940			-	
CW : NIT Review	VF	-	-	-	-	-	2.2	-	Overflow Rates	Butterworth et al., 2016
	Aerated HSSF				-		2.3			
	HSSF				-		0.7			
	Integrated				-		1.7			
	HSSF - tertiary				-		0.2			
	HSSF				8		7.2			

Nitrification										
Technology : Target Contaminant	**Configuration**	**Influent Conc.** (mg/L)	**Effluent Conc.** (mg/L)	**Removal Efficiency**	**Loading Rate - Surface Area** ($gX/m^2/d$)	**Loading Rate - Volumetric** ($gX/m^3/d$)	**Removal Rate - Surface area** ($gX/m^2/d$)	**Removal Rate - Volumetric** ($gX/m^3/d$)	**Comment**	**Source**
CW : BOD, TSS, NIT, DN	-	9.51	0.653	81.9	-	-	-	-	-	Anderson et al., 2015
CW for Lagoon Retrofit : TSS, COD, algae	-	23 9.2	21 10.8	-	-	-	-	-	-	Gschlossl et al., 1998
CW : TSS, NIT, DN, TP	-	0.55	0.02	94%	-	-	-	-	-	Anderson et al., 2013
CW and Trickling Filter : NIT	-	-	-	5.50% 2.1% 27%	0.8 - 4.1	-	-	-	-	Short et al., 2007
Trickling Filter : NIT	-	41-63	-	55-90%	-	-	-	-	-	Avsar et al., 2008
Trickling Filters and Lagoon Expansion : TN, BOD, TSS	-	Existing 18	Upgrade 7	-	-	-	-	-	0.2-2.2 after upgrade of NO_3^-	Archer et al., 2005
Extended aeration lagoon : NIT COD, TSS	-	126.1 (TN) 31.4 (Org.N) -	-	24.3% (TN) 48.2% (Org.N) 37.5% (TAN)	-	-	-	-	-	Abdel-Shafy et al., 2011
Lagoon Expansion : TN, BOD, TSS, TP, FC	-	27 36	21 8	22% 77%	-	-	-	-	-	Picot et al., 2005
Lagoon Retrofit : BOD, TSS NIT, FC	Case 1	Existing 15	Upgrade 1(sum.)-7.4 (wint.)	-	-	-	-	-	-	Archer et al., 2003
	Case 2	Existing 18 [16-23]	Upgrade 5 [0.045-21]							

2.5.2.2 Denitrification

Denitrification is the treatment step following nitrification and is dependent on the effectiveness of the upstream process to ensure complete TN removal. There have been some technology developments on systems targeting denitrification specifically. A table summarizing the principal studies on upgrade technologies for the performance of denitrification in lagoons is found in Table 2-5.

Attached growth reactors are able to sustain the denitrification process. The advantages of this technology are the lower footprint and increased robustness or reliability of the process. These systems are generally designed as post-denitrification and require an external carbon supply, and mechanical mixing (Mendoza-Espinosa and Stephenson, 1999; Rusten et al., 2000; Welander and Mattiasson, 2003; Schlegel and Koeser, 2007; Leyva-Díaz et al., 2015; Torresi et al., 2016; Mattson et al., 2018). The employment of solids separation through a microsieve/discfilter system was found to offer considerable (58%) improvement to TN removal through solids removal in a WRRF using a combined trickling filter/MBBR denitrification process (Wilén et al., 2012).

Wetland systems have shown potential for the removal of TN in wastewater but to a lesser degree than facultative ponds. Correspondingly, multiple studies looking at the implementation of wetlands have found little to no Nitrate/Nitrite (nitrification end-products) in the target lagoon's effluent, highlighting little to no deficiency in this regard. Although studies have demonstrated the denitrification capacity of wetlands in the treatment of landfill leachate, wetlands have not been evaluated in respect to effluent polishing of lagoons for denitrification and TN removal due to limited nitrification being a constraint (Gschlößl et al., 1998; Archer and Donaldson, 2003; Cameron et al., 2003; Kinsley et al., 2007; Crites et al., 2014; Anderson et al., 2015).

Rotating biological contactors have demonstrated aptitude to promote denitrification and simultaneous nitrification-denitrification in wastewater effluent (Tchobanoglous et al., 2014; Hassard et al., 2015); (primary source : WEF 1998).

One of the principal performance gaps in lagoons is the unreliable performance of nitrogen removal, especially nitrification, due to cold temperatures and seasonal variations in performance. Denitrification has been observed to follow the seasonal onset of nitrification, without limit in performance other than by the delayed onset of nitrification in temperate climates. Therefore denitrification in lagoons is consequently also limited by the unreliable nitrification performance of lagoons. A considerable research effort has been undertaken to address this issue across wastewater treatment and attached growth systems, notably the MBBR, have achieved and demonstrated effective and resilient cold-temperature nitrification as well as demonstrated to be an appropriate technology, adaptable to lagoons and rural wastewater treatment (Houweling et al., 2008; Picot et al., 2009).

Table 2-5. Summary of upgrade technologies for lagoon denitrification

Denitrification								
Technology : Target Contaminant	**Configuration Notes**	**Influent Concentration** (mg TN/L u.n.o.)	**Effluent Concentration** (mg TN/L u.n.o.)	**Removal Efficiency**	**Removal Rate - Surface area** ($gN/m^2/d$ u.n.o.)	**Removal Rate - Volumetric** ($gN/m^3/d$ u.n.o.)	**Comment**	**Source**
Discfilter : TP, TSS	-	8.8-12	3.7-7.4	10-15%	-	-	-	Wilen et al., 2012
MBBR : DN	Post-DN	14.2 (NOx)	-	-	2.32	-	-	Torresi et al., 2016
MBBR : NIT, TN	-	67.47	19.02	71.81%	-	-	-	Leyva-Diaz et al., 2015
MBBR : DN	-	-	2.3-4.9	-	4.6 (NOx)	-	Max. rate	Welander and Mattiasson, 2003
					1.5 (NOx)		at 3°C	
SFBBR : COD, NIT, DN, TP	-	-	-	-	up to 2.5	-	-	Schlegel and Koesser, 2007
SAGR : NIT	-	11-12	<2.5	74%	-	-	Steady State	Mattson et al., 2018
BAF : DN	Post-DN	-	-	-	-	Up to 5000	Excess COD	Mendosa-espinosa et al., 1999
CW : BOD,TSS, NIT, DN	Case 1	5.52 (TKN)	2.97 (TKN)	3-89%	-	-	-	Anderson et al., 2015
	Case 2	2.23 (TAN)	1.05 (TAN)					

Denitrification								
Technology : Target Contaminant	**Configuration Notes**	**Influent Concentration** (mg TN/L u.n.o.)	**Effluent Concentration** (mg TN/L u.n.o.)	**Removal Efficiency**	**Removal Rate - Surface area** ($gN/m^2/d$ u.n.o.)	**Removal Rate - Volumetric** ($gN/m^3/d$ u.n.o.)	**Comment**	**Source**
CW for Lagoon Retrofit : TSS,COD, algae	Case 1	0.54	0.07	-	-	-	-	Gschlossl et al., 1998
	Case 2	0.12	0.02					
Lagoon Retrofit : BOD,TSS, NIT, FC	Case 1	Prior 19 (TN)	Upgrade 12 (sum.) -16 (wint.)	-	-	-	-	Archer et al., 2003
	Case 2	Prior 32 [29-37]	Upgrade 16 [10-32]					

2.5.3 Technologies for the removal of phosphorus

Lagoons do not readily sequester phosphorus with the physical and biological mechanisms within these systems. Therefore, chemical additions are typically used to supplement the limited phosphorus removal in order to meet effluent standards. A table summarizing the principal studies on upgrade technologies for the removal of phosphorus in lagoons and on other relevant technologies is found in Table 2-6.

The addition of coagulants in lagoons is used widely to control the level of phosphorus in lagoon effluent. This process is preferred in terms of cost and effectiveness. The addition of metal salts chemically precipitate phosphorus compounds. The process is effective and can readily achieve removal efficiencies of over 90% (Al-layla et al., 1974; Finch and Smith, 1986; Daigger, 2004; Crites et al., 2014; Zhou et al., 2018).

Microsieves have been applied to wastewater systems in conjunction with coagulants for the removal of phosphorus to improve coagulation performance and the removal of solids. The application of discfilters to phosphorus removal is to reduce the process intensity required for coagulation-flocculation of particulates, by removing small flocs using a microsieve. Studies have been able to achieve very low effluent concentrations of phosphorus achieving levels under 0.25 mg/L TP without coagulants and below 80 μg/L TP using coagulants from secondary treatment systems. Applications of this system has mostly remained with mechanized secondary treatment processes and for the reuse of wastewater, with no application as of yet on lagoon systems (Grabbe et al., 1998; Bourgeous et al., 2003; Persson et al., 2006; Tooker et al., 2012; Wilén et al., 2012; Kängsepp et al., 2016; Langer et al., 2017).

Attached growth systems perform phosphorus removal peripherally to their main treatment objectives. In most applications, up to 50% removal of phosphorus is achievable through the biological processes with some effluent concentrations below 0.1 mg-P/L in systems fed from primary mechanized treatment where phosphorus is incorporated in solids mass. To supplement the removal within these technologies, coagulants may be used to fulfill any additional phosphorus removal needs improving removal up to 85% in some cases, dosage depending (Clark et al., 1997; Mendoza-Espinosa and Stephenson, 1999; Rusten et al., 2000; Schlegel and Koeser, 2007; Leyva-Díaz et al., 2015). Trickling filters have also seen co-removal of phosphorus through reduction in ortho-phosphate concentrations, improving removal form 19% to 75% when compared to a facultative pond (Avsar et al., 2008).

Wetlands are host to multiple physical and biological pathways and processes capable of phosphorus removal. In respect to upgrading lagoons, wetlands have seen effective removal of phosphorus from lagoon effluent in free surface wetlands, with 90% TP removal. Reviews covering the removal of phosphorus in wetlands assert that phosphorus removal in wetlands is typically in the range of 40 to 60%, all systems (Gschlößl et al., 1998; Cameron et al., 2003; Vymazal, 2007; Anderson et al., 2013, 2015).

Subsurface systems employing reactive media have been used to sequester phosphorus from lagoon and constructed wetland effluent. There is a large body of knowledge on this topic covering the use of multiple adsorption materials and design parameters for this process. The use of iron and blast-furnace slag adsorption filters has been used as a sorption medium for phosphorus with very effective removal rates, and robust records of performance (Cameron et al., 2003; Genz et al., 2004; Shilton et al., 2006; Valero et al., 2009).

To improve the removal of phosphorus in lagoons, technologies need to be adapted for the application in lagoons, but also need to target performance with respect to the complete effluent and all of its constituents. Subsurface systems like slag filters may have issues with solids clogging that could be problematic, since solids are also an issue in lagoon effluent. Attached growth and wetlands do not target phosphorus effectively as a standalone contaminant, as the removal of this substance in these systems is intrinsically combined with the treatment mechanisms of other contaminants. The use of microsieves, especially in combination with coagulation, have shown exceptional and enhanced phosphorus removal performance, in combination with improving solids removal, both of which are issues problematic to lagoons (Kängsepp et al., 2016; Langer et al., 2017).

Table 2-6. Summary of upgrade technologies for lagoon phosphorus removal

Phosphorus Removal						
Technology : Target Contaminant	**Configuration and Scale**	**Influent Concentration** (mg TP/L)	**Effluent Concentration** (mg TP/L)	**Removal Efficiency / Rate**	**Coagulant Dosing**	**Source**
Discfilter : TP, TSS	Pilot post mechanized WRRF	<0.5	0.03-0.04	-	1.5-2 mg/L PACl, > $FeCl_3$	Langer et al., 2017
Discfilter : TP, TSS	Full scale WRRF	0.31	0.2	22% ±60	No Coagulant	Kangsepp et al., 2016
		0.41	0.14	66%±18	2 mgAL + 1mg/L Poly.	
		0.43	0.13	70%±16	2 mgAL + 1mg/L Poly.	
Discfilter : TP, TSS	Lab scale - + full scale	0.22-0.35	0.27	-	No Coagulant	Wilen et al., 2012
			0.3			
			0.4			
Discfilter : TP	Full scale	0.2-1.5	0.05-0.3	-	30-40 mg/L Alum	Tooker et al., 2012
		0.4-1.8	<0.05-0.1		35-50 mg/L Ferric	
		1.13-0.5	<0.1		30 mg/L Alum	
		0.7, 0.8, 0.65	0.35, 0.20, 0.10		30-70 mg/L PACl	
		0.9, 1.3, 1.4	0.05		52 mg/L Ferric	
Discfilter : TSS, TP	Post MBBR - pilot	0.2-0.7	<0.1	-	No Coagulant	Presson et al., 2016
MBBR : NIT, TN	Pilot at WRRF	8.31	4.15	50%	No Coagulant	Leyva-Diaz et al., 2015
SFBBR : COD, NIT, DN and TP	Full scale as mechanized treatment, versus AS	-	-	20-50%	No Coagulant	Schlegel and Koesser, 2007
BAF : Review	-	-	-	35%	No Coagulant	Mendosa-espinosa et al., 1999

Phosphorus Removal						
Technology : Target Contaminant	**Configuration and Scale**	**Influent Concentration** (mg TP/L)	**Effluent Concentration** (mg TP/L)	**Removal Efficiency / Rate**	**Coagulant Dosing**	**Source**
BAF : TP	-	-	-	85%	1 : 1.14 P to Ferric Sulphate	Clark et al., 1997
CW : BOD, TSS, NIT, DN	Pilot at secondary lagoons	3.96	1.855	49.80%	No Coagulant	Anderson et al., 2015
CW : TSS, NIT, DN,TP	Full scale lagoons	1.41 average	0.038	94%	No Coagulant	Anderson et al., 2013
		3.1 peak	0.03	99%		
CW and Trickling Filters : TP	Pilot	4.1-12.6 g Ortho/m^3/d	-	-10 g orthoP /m^3/d	No Coagulant	Short et al., 2007
				-5.1 g orthoP /m^3/d		
				-9.3 g orthoP /m^3/d		
CW for Lagoon Retrofit : TSS, COD, algae, TP	Full scale case studies	Case 1		-	No Coagulant	Gschlossl et al., 1998
		6.9	5.1			
		Case 2				
		5.3	6.9			
Trickling Filter : TP	Pilot	12-20	-	65-85%	No Coagulant	Avsar et al., 2008
Lagoon expansion : N, BOD, TSS, TP, FC	Full scale	Prior		23%	No Coagulant	Picot et al., 2005
		14.7	11.3			
		Upgrade		37%		
		7.9	5			
BFS filter : TP	Pilot - tied to lagoon	-	2	3.2 g TP/kg BFS	Adsorption	Valero and Mara, 20010
BFS Filter :TP	Full scale 11 years	-	-	1.18-1.23 g TP/kg BFS	Adsorption	Shilton et al., 2006

2.5.4 Technologies for the removal of pathogens

Pathogen removal is important for human and ecological health. The removal of pathogens is generally very good in lagoon systems because of the use of maturation ponds and the occurrence of high pH in facultative ponds. These systems may not require effluent disinfection. Wetlands have demonstrated good removal capacity for removal of fecal coliforms, with median reduction of 2 log removal (99%), while total coliform followed a more varied trend (Boutilier et al., 2009; Kadlec, 2009; Anderson et al., 2015). Batch coagulation in lagoons has found 3 log removal of fecal coliforms, although the use of coagulation requires a high level of operator experience, and is very operationally intensive, making it incompatible with lagoon operations (Finch and Smith, 1986; Crites et al., 2014; Verbyla and Mihelcic, 2015).

Research on the removal of emerging contaminants has characterised relative performance between systems, including rotating biological contactors, MBBR's, wetlands, lagoons, and activated sludge, with lagoons being an effective removal technology for these substances as well (Anderson et al., 2015; Matamoros et al., 2016; Torresi et al., 2016).

2.5.5 Technologies for the removal of solids

Solids generation is one of the principal challenges facing lagoon systems. The generation of solids in lagoons through algae growth and pond detritus has highlighted the need for effluent polishing targeting suspended solids, which has mostly focused on the removal of algal solids (Middlebrooks, 1995; Pearson, 2003; Khorsandi et al., 2014). A table summarizing the principal studies on upgrade technologies for the removal of solids in lagoons and other relevant technologies is found in Table 2-7.

The solids removal capacity of wetland systems and particle distribution and speciation has been studied along with influent/effluent TSS correlations to assess the solids removal performance of wetlands (Boutilier et al., 2009; Kadlec, 2009). Specifically in a full scale study of a wetland system for lagoon effluent polishing configuration, the solids removal capacity of the wetland varied considerably and was unreliable (Cameron et al., 2003). The use of constructed wetlands for lagoon effluent polishing targeting algae removal is not effective. The sequestration of algae, particularly within subsurface flow wetlands, induces the decomposition of algae and a subsequent release of BOD and nitrogen in the effluent (Gschlößl et al., 1998). In a comparative study looking at lagoons and wetlands, trickling filters have been found to provide some removal of up to 60% of chlorophyll α, reports providing mixed results with respect to the generation of BOD, TAN and H_2S (Middlebrooks, 1995; Short et al., 2007).

Coagulation has also been studied as a means to control solids and algae in lagoon effluent. Coagulation is known to be able to agglomerated particles ranging from 0.1 to 10 µm particles, and studies on lagoon specific use of coagulation have obtained mixed results and proposed doses (Al-layla et al., 1974; Harrelson et al., 1982; Audrey D. Levine, 1985; Finch and Smith, 1986; Fitzpatrick and Gregory, 2003; Crites et al., 2014). A study by (Golueke and Oswald, 1965) found that effective coagulation and subsequent flocculation of algae occurred at a dosing of 90 mg/L of Alum in a batch coagulation of a lagoon cell, while (Finch and Smith, 1986) have found that batch coagulation at a dose of 300 mg/L achieved 90% suspended solids removal, and considerable improvement on cBOD, and ortho-P removal. Overall coagulation is very operationally complex and requires operators with considerable experience. Because of this, the use of coagulation for suspended solids control is not compatible with lagoon systems (Environmental Protection Agency, 2011; Crites et al., 2014). Furthermore, there is also a knowledge gap on whether the removal of phosphorus through coagulation upstream of the system contributes to algae control in lagoons which could provide a peripheral means of solids control due to the role that algae solids play in lagoon effluent.

Dissolved air flotation is a separation technology that uses combined air flotation and coagulation. Studies have shown some mixed effectiveness in algae removal in treating wastewater lagoon effluent. Effectiveness of this technology is dependant on a number of operational parameters, such as coagulant dose, recycle rate, flowrate, and flocculation time (Harrelson et al., 1982; Buisine and Oemcke, 2001; Yap et al., 2012).

Intermittent sand filtration is an inexpensive, simple upgrade option for the removal of algae in lagoon systems. The performance of these systems has been studied and applications have observed considerable variations in effluent quality, which are not compatible with current effluent targets and regulations (Rich and Wahlberg, 1990; Truax and Shindala, 1994).

Additionally, the operational requirements of this technology are not compatible with winter operations of lagoons in temperate climates.

Membranes are a physical separation process that has seen increased use in water treatment as an advanced treatment process. These systems are well-developed for this application. Membrane systems are prone to fouling and have considerable maintenance requirements even in water treatment. There are a limited number of studies looking at membrane applications for the polishing of lagoons. Due to high energy costs and increasing operational intensity due to the fouling potential of membranes, the overall operating costs likely fall beyond what is appropriate for lagoon wastewater treatment technologies (Fan et al., 2008; Nguyen et al., 2009; Molinos-Senante et al., 2012).

Available technologies for lagoons have demonstrated a limited to moderate effectiveness in the solids removal of lagoons, although the most effective technologies have demonstrated limited adaptability to lagoon wastewater treatment due to excessive operational intensity, sludge management issues and required footprint.

Table 2-7. Summary of upgrade technologies for lagoon TSS removal

TSS Removal							
Technology : Target Contaminant	**Configuration and Scale**	**Influent Concentration** (mg/L)	**Effluent Concentration** (mg/L)	**Solids Loading** (gTSS/m^2/h u.n.o.)	**Hydraulic Loading**	**Removal Efficiency**	**Source**
Discfilter : TP, TSS	Pilot post mechanized WRRF	9.4-22	3.2-4.8	-	-	-	Langer et al., 2017
Discfilter : TP,TSS	Full scale WRRF	18.1	3.9	28	-	75%	Kangsepp et al., 2016
		31.9	2.3	48	-	92%	
		17.7	2.7	34	-	80%	
Discfilter : TP, TSS	Lab and Full scale	4.2-9.5	2.5-3.4	-	-	-	Wilen et al., 2012
Discfilter : TP	Full scale	75-350	<<15 mg/L with ferric sulfate	-	-	-	Tooker et al., 2012
Discfilter : TSS, TP	Post MBBR - pilot	9-50	2-5	-	-	-	Presson et al., 2016
Discfilter 10um : TSS	Post Activated Sludge	-	0.25-0.9	5-32 kg/m^2/d	7-15 m/h	-	Bourgeous et al., 2003
MF - cross flow : TSS	Lab scale	-	-	-	-	96-98% NTU 100% Algae	Al malack et al., 1998
MBBR : NIT	Pilot at aerated lagoon	7.3	16.8-21	-	-	-	Young et al., 2017
MBBR : COD	Lab scale and pilot	-	52-136	-	-	-	Sicilliano and De Rosa, 2016
MBBR : NIT, TN	Pilot at WRRF	87.16	5.6	-	-	93.57%	Leyva-Diaz et al., 2015

TSS Removal								
Technology : Target Contaminant	**Configuration and Scale**	**Influent Concentration** (mg/L)		**Effluent Concentration** (mg/L)	**Solids Loading** ($gTSS/m^2/h$ u.n.o.)	**Hydraulic Loading**	**Removal Efficiency**	**Source**
MBBR -post secondary: NIT	Pilot	-		-	1015-1139 $g/m^3/d$	-	-	Rusten et al., 2000
CW : BOD,TSS, NIT, DN	Pilot at lagoons	29		7.25	-	-	56.6%	Anderson et al., 2015
CW : TSS, NIT, DN, TP	Full scale lagoons	21.2		7	-	-	61%	Anderson et al., 2013
CW for Lagoon Retrofit : TSS, COD, algae	Full scale	Case 1	16.5	12.7	-	-	23.10%	Gschlossl et al., 1998
		Case 2	21.3	8.1			61.90%	
CW: TSS	Pilot	-		-	22-223 $mg/m^3/d$	-	37%	Short et al., 2007
Lagoon: TSS							31%	
Trickling Filter : TSS							64%	
Trickling Filter : TSS	Pilot	50-145		-	-	-	85% to 95%	Avsar et al., 2008
Trickling Filter : COD, Chl. A	Lab scale	64.8 - 65.7		1.5-1.8	-	0.5 $m^3/m^2/d$	-	Kaya et al., 2007
				2.5-2.8		2 $m^3/m^2/d$		
				3.6-22.2		4 $m^3/m^2/d$		
Trickling Filters and Lagoon Expansion : TN, BOD, TSS	Full scale case studies	-		88 to 66 (post upgrade)	-	-	-	Archer et al., 2005
Extended Aeration Lagoon : NIT, COD, TSS	Upgrade of existing lagoon	479.3		121	-	-	74.9% to 80%	Abdel-Shafy et al., 2011
Lagoon Expansion : TN, BOD, TSS, TP, FC	Full scale	251		136	-	-	46%	Picot et al., 2005
		266		109			59%	

TSS Removal							
Technology : Target Contaminant	**Configuration and Scale**	**Influent Concentration** (mg/L)	**Effluent Concentration** (mg/L)	**Solids Loading** ($gTSS/m^2/h$ u.n.o.)	**Hydraulic Loading**	**Removal Efficiency**	**Source**
Lagoon Retrofit : BOD, TSS, NIT, FC	Full scale	-	56	-	-	-	Archer et al., 2003
			50				
			59 (29-110)				
			40 (28-70)				

2.6 Microsieves and discfilters as a solids and phosphorus removal technology

Microsieves are a physical separation technology that have been developed for the treatment of wastewater for the removal of solids. There have been widespread uses of this technology in Canada, the US and especially the EU with over 300 installations, although there are limited reports in literature on the performance of these systems (Golueke and Oswald, 1965; Al-layla et al., 1974; Harrelson et al., 1982; Grabbe et al., 1998; Bourgeous et al., 2003; Remy et al., 2014).

Operational advantages of microsieves include the low cost, simplicity of operation, limited maintenance requirements, operational flexibility and adaptability, high hydraulic flexibility, low headloss, small footprint, and low energy requirements. Microsieves present an advantage over membrane systems with their higher hydraulic flexibility (higher allowable variation in hydraulic loading, which signifies less reliance on flow bypass to convey flow and less process interruptions). Impact assessments have also shown that the effluent quality improvement provided by membrane processes compared to microsieves is marginal in wastewater treatment processes (Remy et al., 2014). Microsieves also have comparable performance to dissolved air flotation (DAF) systems in the removal of algae, at a lesser operational intensity. Some systems have also demonstrated improved robustness compared to ballasted sedimentation with respect to removal of algae and solids (Tooker et al., 2012).

Advances and developments in filter materials (lower pore-size, better materials, and decreased clogging susceptibility) have improved the effectiveness of microsieves, improving the overall performance, reliability and robustness of this technology over its history. Various materials are used in these processes, including needle-felt cloths, pile-on cloths, and woven polyester cloths of various pore-sizes (Wilén et al., 2012; Langer et al., 2017). The choice of material pore-size is reflected in the compromise between separation efficiency, hydraulic capacity and clogging potential (Wilén et al., 2012). Coagulation and flocculation have often been used in conjunction with this technology to provide enhanced removal of suspended solids and phosphorus (Bourgeous et al., 2003; Tooker et al., 2012; Kängsepp et al., 2016; Langer et al., 2017).

Discfilters, similar to the unit(s) developed by Hydrotech AB (now Veolia Water Technologies), are solids removal technology that employ microsieves as the filtration medium. The technology uses a set of modular discs equipped with filter cloths to remove particulates under gravity flow. The system backwash component uses pressurized filtered water jets to clean the filter cloth periodically, with less than 2 to 5% of the production water. Typical filter cloths used in conjunction with this system are woven polyester filter cloths, with sizes including 40, 20, 15, 10 µm, and other cloth materials in development, which are fouling resistant, chemical resistant and generally durable. These systems have seen applications in municipal wastewater but also in industrial and food processing applications. Discfilters specifically have been applied in a handful of Canadian municipalities with capacities up to 240 MLD. Discfilters used for lagoon discharge flowrate typically revolve around 10 MLD (Veolia Water Technologies, Sweden).

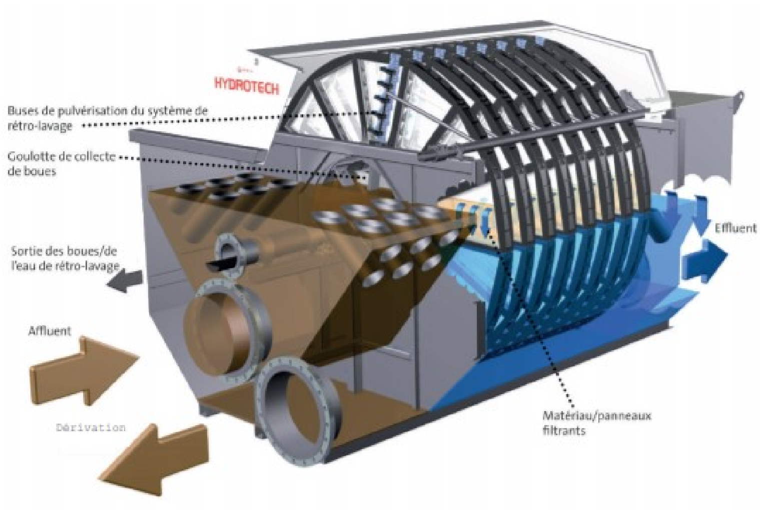

Fig. 2-1. Schematic of a full scale discfilter system (Veolia Water Technologies, n.d.)

Recent studies on the use of discfilters have employed these systems following secondary mechanized treatment trains, with strict effluent quality targets for solids and phosphorus. Applications included solids removal and concurrent phosphorus removal for wastewater reuse and the removal of difficult-to-settle suspended solids in CAS and MBBR effluent polishing.

Discfilters have also demonstrated potential for effective algae removal in lagoon systems, as the separation process is not affected by the adverse effects related to the accumulation and decomposition of algae, as is the case in HSSF wetlands (Gschlößl et al., 1998). Overall the technology is robust for TP removal and for TSS removal but has yet to be demonstrated and applied to lagoon systems.

Literature on this system reports on the removal suspended solids and total phosphorus. Most studies employed multiple filters, but the 10 µm twill woven polyester filter cloth is common to all studies on mechanized treatment effluent. Quantitatively, the 10 µm cloth could achieve an effluent concentration of 1 mg SS/L without coagulants in pilot scale, with an effluent TSS concentration below 5 mg SS/L achievable in full scale. TP removal in these conditions ranged from 25-55% with an effluent concentration below 0.3 mg P/L, with performance depending on the characteristics of the filter influent (primary, secondary, etc.). In studies with the use of coagulants in the treatment of secondary effluent, TSS removal saw only marginal improvements from already low influent concentrations, while TP removal saw improvements with 86% removal and with effluent concentrations below 0.1 mg P/L. A threshold of 0.08 mg P/L was achievable with optimisation of coagulant and flocculant dosing (Persson et al., 2006; Wilén et al., 2012; Kängsepp et al., 2016; Langer et al., 2017).

Discfilter performance is characterized by a well-defined particulate cut-off, with cake filtration providing improved removal of smaller particles. Consequently, the performance of these systems depends on the influent TSS concentrations as well as on the characteristics of influent wastewater. The dependence on the influent TSS concentration increases with increase in cloth pore-size. It has also been demonstrated that discfilters can produce smaller colloids in the effluent. This is attributed to retained flocs breaking up, highlighting the impact of floc strength on filtration efficiency. This phenomenon was more prevalent on smaller pore-size cloths, and in the treatment of secondary effluent (Persson et al., 2006; Tooker et al., 2012; Wilén et al., 2012; Kängsepp et al., 2016; Langer et al., 2017). Peripherally to this systems principal treatment objectives, concurrent removal of COD and TN with suspended solids occurred, but pathogens were mainly unaffected (Wilén et al., 2012; Langer et al., 2017).

Discfilters have low specific energy requirements: under 34 Wh/m^3 with coagulants and flocculants, or 13 Wh/m^3 for discfilter operating in gravity flow. The technology also has a high flow recovery, with less than 2% to 5% of the water used for backwash. Discfilters have a 50-70%

smaller land footprint than rapid sand filters, and also share advantages with other microsieve technologies including low maintenance requirements, low operational intensity, and considerable operational flexibility (Persson et al., 2006; Tooker et al., 2012; Wilén et al., 2012; Kängsepp et al., 2016; Langer et al., 2017).

2.6.1 Pilot discfilter unit

The discfilter unit used in this study is a "mini-disc" discfilter: it is a custom-built unit sized for flowrates seen in pilot scale experiments (Fig. 2-2). This section will cover some of the technical aspects related to the operation of this unit that may not be evident to readers unfamiliar with this unit. A cross-section of the unit describing the process mechanics is shown in Fig. 2-3.

Fig. 2-2. Mini-disc unit pilot configuration

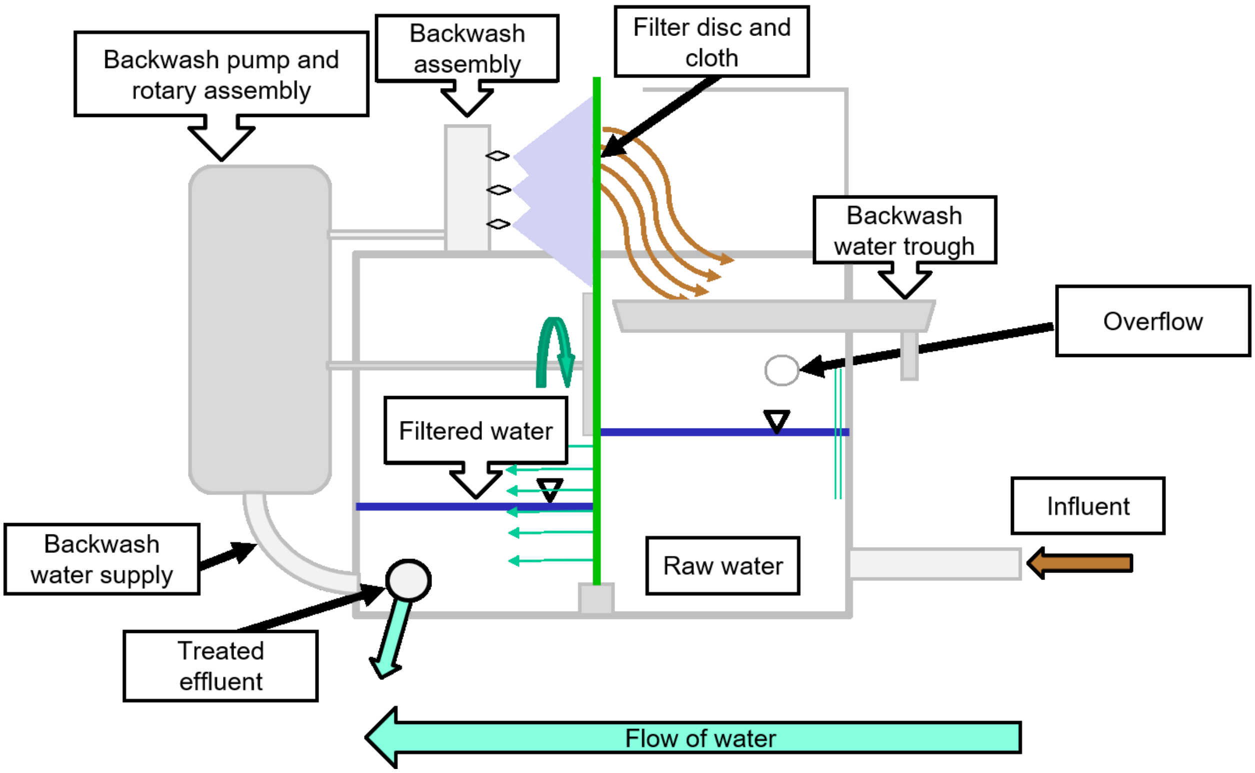

Fig. 2-3. Pilot discfilter unit section and process schematic

The mini-disc unit uses microsieves to strain out solid particles. In these units, like with discfilters, the pressure to drive water through the microsieve is provided through a head differential between the inlet and outlet side of the filter, provided by gravity (Fig. 2-3. Pilot discfilter unit section and process schematicFig. 2-3).

The filtration area of this pilot unit is the area submerged below the water level of the raw water tank. For this pilot unit, the effective filter area was of 0.14 m^2, and the submerged filter material is renewed and cleaned by backwashing at each cycle.

The backwash process is of a fixed duration and activates based on a set water level of the raw water side. During the cycle time, the backwash process rotates the assembly and cleans the entire filter disc with filtered water to remove accumulated detritus on the filter material.

Backwash frequency (BW%) corresponds to the fraction of total cycle time in which backwash was running. For example, at 10% backwash frequency, the backwash cycle will be active for 10%

of a complete cycle time (from the start of one backwash cycle to the start of the next) (Equation 1).

$$BW(\%) = \frac{time_{BW}}{time_{BW} + time_{filtration}} \; (Eqn.1)$$

In normal conditions, the water level will be able to return below the critical level and the backwash will stop after the fixed duration. In an overflow condition however, this does not occur, and the backwash frequency is effectively of 100%. In this study, to characterize the hydraulic capacity of the filters, backwash frequency was used as a metric of hydraulic capacity of the filter.

2.7 References

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3 Removal of wastewater lagoon solids using discfiltration

3.1 Abstract

The microsieving discfilter technology was investigated at the pilot scale. The pilot was configured to treat the effluent from a municipal wastewater multi-lagoon facility consisting of two facultative lagoons and a third seasonally aerated lagoon to mitigate hydrogen sulfide release. The 10 µm filter, operated without chemical enhancement, demonstrates 60.1 ± 22.6% removal of effluent TSS during periods of operation without aeration of the third lagoon. Aeration of the third lagoon of the multi-lagoon system prior to discharge rendered the 10 µm filter cloth ineffective with respect to solids removal. The 5 µm filter cloth performed effective non-chemically enhanced removal of solids even during aeration of the lagoon, removing 68.2 ± 9.85% of effluent TSS. The greater performance of the 5 µm filter was achieved at the expense of a lower maximum conveyance capacity than the 10 µm filter. The 10 µm and 5 µm filters decreased the effluent TP concentrations by 0.14 mg-P/L and 0.13 mg-P/L, respectively. For algae characterized as chlorophyll α, the analysis showed removal from influent concentrations of 10.25 ± 4.19 µg/L to concentrations of 4.61 ± 1.28 µg/L for the 10 µm filter, and 4.10 ± 0.65 µg/L for the 5 µm filter. Overall, the microsieving technology may be useful for reducing effluent solids and phosphorus concentrations from lagoons.

3.2 Introduction

Current challenges facing wastewater resource recovery facilities (WRRFs) include increased loadings, limited land, energy, and capital resources, and increasingly stringent effluent regulations. Wastewater treatment lagoons are the predominant passive wastewater treatment technology in rural communities and have demonstrated good performance for the treatment of municipal wastewater with respect to biological oxygen demand (BOD) and pathogens, but face challenges in the removal of suspended solids, phosphorus, and total ammonia-nitrogen (TAN) (Pearson, 2003; Van Dyke et al., 2003; Environmental Protection Agency, 2011; Crites et al., 2014; Mavinic et al., 2018a; WEF, 2018). Suspended solids (as total suspended solids (TSS)) and phosphorus are two of the four principal contaminants targeted by the increasingly stringent regulations in Canada, the US and the EU. This highlights the need to upgrade rural, conventional treatment systems currently in place to improve effluent quality, ensure compliance, and limit anthropogenic impacts on natural waters. (Oleszkiewicz and Barnard, 2006; Oleszkiewicz et al., 2015; Mavinic et al., 2018a). Lagoons in Canada and in the US represent about half of the publicly owned WRRFs (Environmental Protection Agency, 2011; Mavinic et al., 2018a; Statistics Canada, 2018).

Although lagoons present mechanisms for the removal of wastewater-borne solids, the long retention times, availability of organic matter and nutrients create conditions favourable to the proliferation of algae in these systems and hence an increase in the suspended solids of these systems (Middlebrooks, 1995; Pearson, 2003). Algal suspended solids generation poses a significant and widely-recognized problem in wastewater treatment lagoons, as they contribute to 90% of particulate BOD and to particulate solids impacting receiving waterways. The proliferation of algae in lagoons coupled with the settling of raw wastewater solids and other active biological processes account for the dynamic characteristics of suspended solids within lagoons.

Upgrade technologies for lagoons need not only meet discharge requirements, but also compatibility with rural and lagoon-specific treatment operations. The realities of this requirement dictate that these upgrade systems need to be adapted for low-flow conditions and have reasonable and compatible requirements for maintenance, energy, and land resources as well as compatibility with monitoring requirements (Muga and Mihelcic, 2008; Environmental Protection Agency, 2011; Molinos-Senante et al., 2012; Vera et al., 2013; Remy et al., 2014; WEF, 2018). Researchers have investigated multiple methods for the treatment of lagoon solids, including coagulation, constructed wetlands, dissolved air flotation, intermittent sand filtration, and membranes (Al-layla et al. 1974; Levine et al. 1985; Buisine and Oemcke 2001; Crites et al. 2014; Fan et al. 2008; Finch and Smith 1986; Fitzpatrick and Gregory 2003; Harrelson et al. 1982; Molinos-Senante et al. 2012; Nguyen et al. 2009; Remy et al. 2014; Rich and Wahlberg 1990; Truax and Shindala 1994; Yap et al. 2012). These tested systems have demonstrated limited to moderate effectiveness in the removal of lagoon specific solids including algae, and have varied levels of compatibility with lagoon systems (Middlebrooks et al., 1974; Truax and Shindala, 1994; Buisine and Oemcke, 2001; Pearson, 2003; Yap et al., 2012).

Microsieves as a technology have been installed as solids removal systems to mechanised treatment facilities since the 1980's, with recent material technological improvements having demonstrated performance gains (Grabbe et al., 1998; Bourgeous et al., 2003; Wilén et al., 2012). In particular, microsieve-like physical separation processes have seen developments of new material technologies including pile-on filter cloths, needle felt cloths and woven polyester cloths (Bourgeous et al., 2003; Wilén et al., 2012). The discfilter technology, a type of microsieve, is a low energy and low footprint mechanized treatment process that has shown an ability to effectively remove solids from secondary treatment effluent (Persson et al., 2006; Tooker et al., 2012; Wilén et al., 2012; Kängsepp et al., 2016; Langer et al., 2017). Because of these operational benefits, the discfilter technology may therefore be a promising microsieve technology that fulfills the compatibility requirements of rural and lagoon WRRFs, as well as a potential effective technology for solids removal. There is however currently a fundamental lack of literature and knowledge on the utilization of the microsieving technology applied to municipal lagoons. Therefore, the overall objective of this study is to assess the removal of suspended solids in lagoon effluent using a pilot-scale discfilter unit, in the optic of guaranteeing compliance and meeting strict effluent discharge requirements of existing lagoon systems. To fulfill this objective, a comparison of two discfilter filters were studied across various hydraulic and solids loading rates with the assessment of hydraulic performance, solids removal performance and characterization of peripheral performance benefits for the removal of phosphorus, and algae, characterized as Chlorophyll-α.

3.3 Materials and methods

3.3.1 Site description

A discfilter pilot-scale treatment plant was installed at the Casselman WRRF, (Casselman, Ontario, Canada) and was fed effluent wastewater from the lagoon facility. The Casselman lagoon facility consists of three cells: two facultative cells followed by a seasonally-aerated maturation cell to remove sulfides prior to discharge. Discharge at the Casselman WRRF occurs seasonally. This facility treats separated sanitary sewage and hauled septage. The lagoons have a rated capacity of 2 113 m3/d, and use alum dosing of 163 mg/L dosed at the inlet of the lagoon for phosphorus control purposes. It is noted that, although alum dosing occurs at the lagoon, further phosphorus removal may be required at this facility to meet future stringent effluent standards. The lagoon effluent wastewater used to feed the discfilter pilot plant in this study was characterized as shown in Table 3-1. These lagoon effluent characteristics are indicative of a well operated lagoon facility.

Table 3-1. Water quality analysis of the lagoon effluent supplied to the pilot plant.

Parameter	Range of Values Observed	Units
Temperature	4.7 – 8.0	°C
pH	7.0 -8.0	-
Dissolved Oxygen	4.8-5.0	mg/L
TSS	3.2-72.8	mg/L
VSS	b.d.l.	mg/L
Turbidity	2.0-200	NTU
Total Phosphorus	0.15-0.83	mg-P/L
Orthophosphates	0.00-0.30	mg/L
Chlorophyll α	4.05 – 23.37	μg/L
Total Coliforms	365.4 – 7590.0	MPN/100mL
Phycocyanin	b.d.l.	μg/L

b.d.l: Below detectable limit

3.3.2 Experimental plan

To establish an overall performance assessment of the discfilter system for polishing of lagoon effluent, an analysis was conducted on two filters, 10 µm and 5 µm nominal pore-size filters (Veolia Water Technologies, Sweden). The individual pilot-scale filter cloths provided an active filtration area of 0.14 m^2. The 10 µm filter cloth used in this experiment was a 10 µm pore size filter and is manufactured from twill weave monofilament polyester (Persson et al., 2006). The 5 µm filter used in this study was an experimental material that currently remains in development.

In order to gather data on an appropriate sampling method, prior to this study, the filters were wetted and tested for a preliminary assessment over 3 weeks to isolate loading effects and potential sampling issues affecting the discfilter system. From this assessment, it was apparent that wastewater supplied from the water column to the pilot plant had insufficient suspended solids to achieve the targeted loading rates for a steady-state loading condition of the discfilter. As such, in this study, solids were entrained from various depths within the lagoon, including the entrainment of solids from the lagoon bed itself, to create a transient loading condition of the discfilter. The transient loading was performed to assess the performance of the discfilter unit with the two filters across a range of solids characteristics from the lagoon. To entrain solids in the filter, the bed of the lagoon at the pump location was agitated with high pressure air bubbles to resuspend solids in the water column. Turbidity readings coming into the system were then monitored, and sequential sampling was performed at similar turbidity measurements and intervals, on the downward limb of the transient targeting a representative solids concentration range for lagoons.

The study sampling period was selected to assess the performance of discfilters applied to lagoons during the seasonal discharge period. The timeline of sampling and sampling conditions of this study are representative of the lagoon in discharge conditions**Table 3-2.** Timeline of sampling Table 3-2.

Table 3-2. Timeline of sampling

Filter	Sampling Dates	Water Temperatures
10 µm non-aerated	October 4^{th} and 9^{th}, 2018	8.0°C and 7.6 °C
10 µm aerated	November 5^{th}, 2018	4.7 °C
5 µm aerated	October 24^{th}, 2018	6.2 °C

Three testing phases were performed to assess the performance of the discfilter filters across hydraulic and solids loading. The first testing phase studied the performance of the 10 µm filter and operationally focused data on the discfilter, with the aeration system of the third cell disengaged. The second testing phase studied the 10 µm filter with the aeration system of the third cell in operation. The third testing phase studied the 5 µm filter performance with the aeration system of the third cell in operation. Sampling was performed targeting two distinct hydraulic loading rates, representing a conventional and elevated hydraulic loading. Sampling of the first, second and third phases included a minimum of 36 samples collected from the inflow, outflow, and backwash water of the filter. Triplication for sampling and water quality analysis was performed for at least 40% of the samples during each of the three phases to quantify sampling and analytical error in the study.

3.3.3 Discfilter pilot unit

The pilot plant used in this study housed a Hydrotech® Mini-disc discfilter unit (Veolia Water Technologies, Sweden) (Langer et al., 2017). The discfilter unit itself consists of a single disc for filtration and is equipped with automatic backwash that uses filtered water, and is initiated based on headloss through the cloth. This backwash operation uses approximately 2% to 5% of the total filtered water produced. Backwashing in this pilot unit occurs concurrently and without interruption of the filtration process.

3.3.4 Analytical methods

The operational parameters considered for analysis were hydraulic loading, backwash frequency (duration of the backwash cycle), and concentrations of suspended solids, chlorophyll α, and phosphorus (total and reactive) for all three phases of sampling.

Influent, effluent and backwash samples were analysed for TSS and VSS (SM 2540 (TSS,VSS)); total phosphorus (TP), orthophosphates (SM-4500 (phosphorus)); chlorophyll α (modified SM-10200 H (chlorophyll α)); (APHA, 2017; Martens, 2018). Colorimetric methods were performed using a DR 6000 spectrophotometer (Hach; Loveland, CO).

Backwash samples were also analysed for retained algae identification. Images of algae were acquired using a Zeiss LSM510/Axio imager M.1 confocal microscope (Carl Zeiss, Canada) with a ×63 water submersion objective.

Turbidity was measured in real time in the field using a Hach Solitax SC probe (Hach; Loveland, CO). Flowrate was measured using an electromagnetic Krohne IFC 010 D flowmeter (KROHNE Messtechnik GmbH; Duisburg, Germany). Temperature was measured using a Hach HQ40D handheld field meter, and a Hach LDO101 DO probe (Hach, Loveland, CO). Maintenance on the real-time probes, flowmeter and sampling conduits was performed as specified by the manufacturer and to mitigate contamination of samples and ensure accuracy of measurements.

3.3.5 Statistical methods

The paired student's t-test was used with a critical value of $p < 0.05$ to establish statistical significance. Average values in this study are presented along with the standard deviation. Correlations and multiple regression analyses were applied between various operating and performance variables in this study.

3.4 Results and discussion

3.4.1 Influent TSS and hydraulic loading range

The influent solids concentrations for the first study phase (10 µm filter in operation with the third lagoon cell not being aerated) were in the range of 3.2 to 72.8 mg-TSS/L. For the both the second and third study phase (10 µm filter in operation with the third lagoon cell being aerated, and 5 µm filter in operation with the third lagoon cell being aerated) the influent solids concentrations ranged from 7.6 to 37.2 mg-TSS/L (Fig. 3-1). The difference in the range of TSS values entering the pilot plant is likely due to the aeration effects in the third cell. The three phases of the study were performed at both a conventional low hydraulic loading rate (LR) ranging between 4.09 and 6.11 m/h and at an elevated high hydraulic loading rate (HR) ranging between 6.85 to 9.21 m/h (Fig. 3-2A). Impact of water temperature on the solids removal performance of the discfilter was assessed to a limited extent by comparing the TSS removal performance of the 10 µm filter between the preliminary phase of testing and the solids removal performance from data with similar TSS loadings (<80 gTSS/m2/hr). The analysis demonstrated that no significant correlation existed between water temperature and TSS removal on the 10 µm filter (r = 0.098, p =0.656). A more detailed analysis should be undertaken to determine the effect of water temperature on both filters, across a continuous range of temperatures, to better understand how this temperature impacts filter performance. It is plausible that significantly lower temperatures may induce material changes on the filters, modifying system performance. Water temperatures during pilot operation ranged from 4.7°C to 8.0°C across all samples. The range in TSS concentrations and hydraulic loading resulted in an overall range of solids loadings between 25.2 to 574.1 g-TSS/m2/h. This range of loading rates are range from conventional to elevated operating loadings for the discfilter technology and the TSS concentrations were in the typical range for lagoon operations (Mara, 2004).

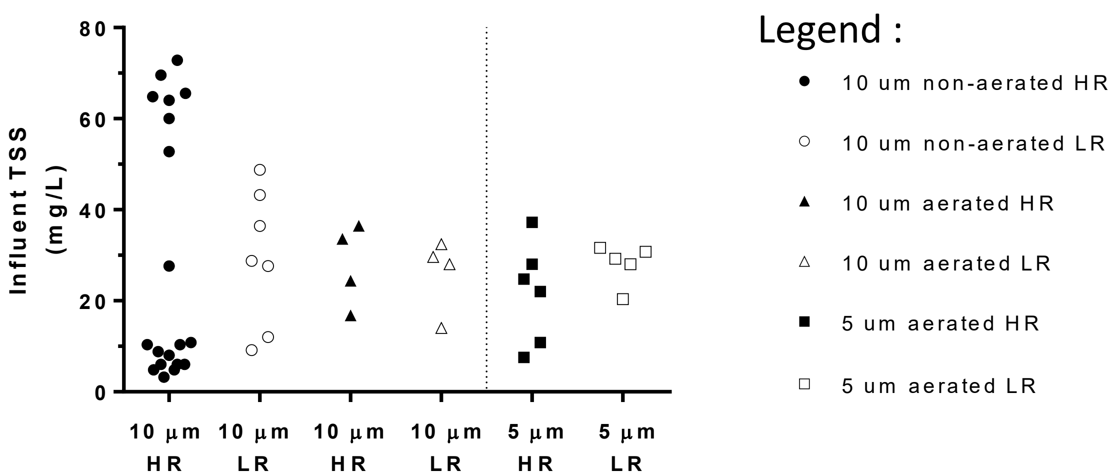
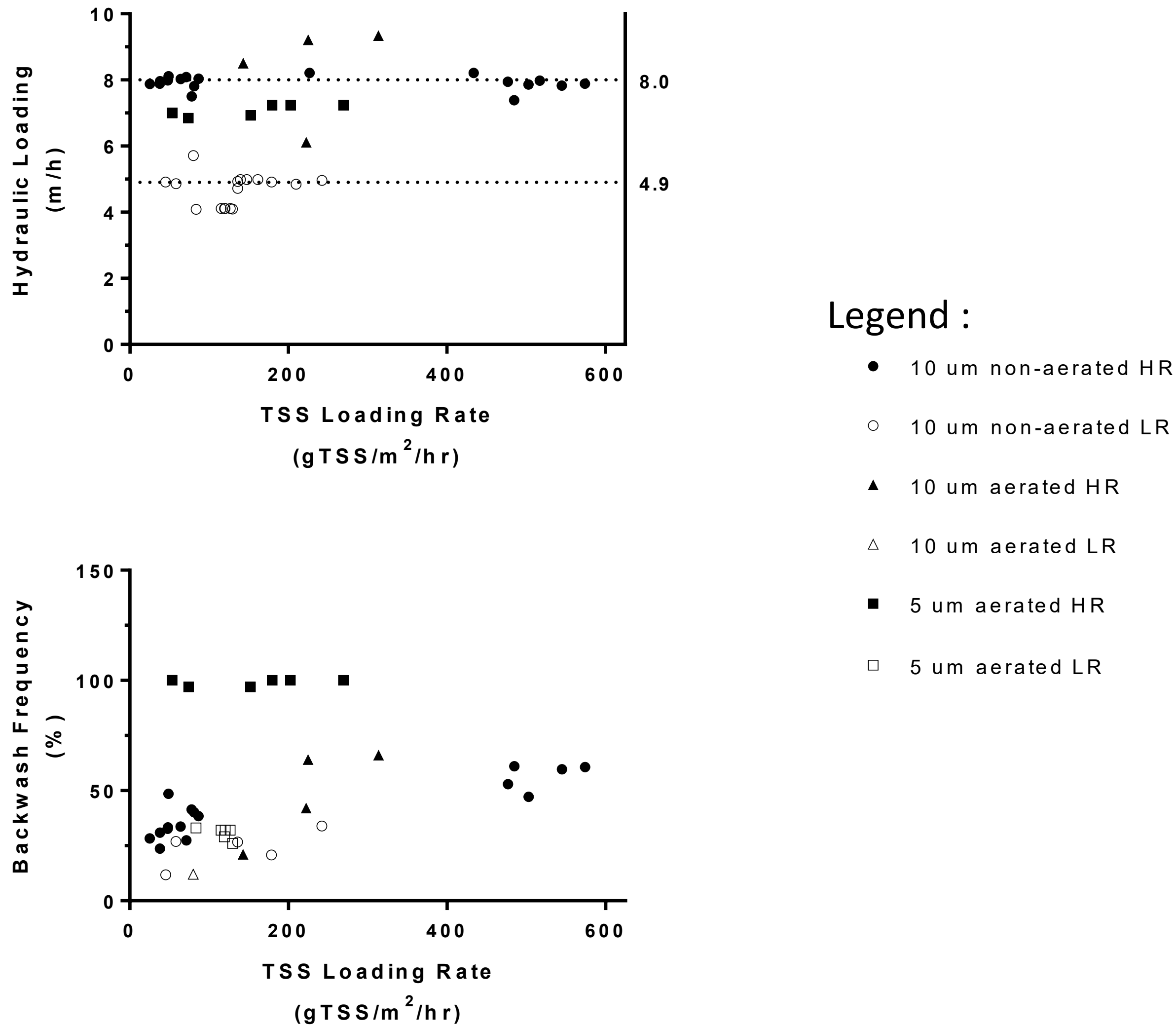


Fig. 3-1. Range of influent TSS concentrations across cloth types at various hydraulic loading rates

3.4.2 Hydraulic loading capacity

Backwash frequency, measured as the percentage of time that backwashing is engaged during operation, is the principal metric for measuring the in-use hydraulic load capacity of the discfilter (Langer et al., 2017). The loading applied to the filters resulted in backwash frequencies of 11.8% to 61.0% for the 10 µm filter without aeration of the third lagoon cell, 12.2% to 66.0% for the 10 µm filter with aeration of the third lagoon cell and of 26.0% to 100% for the 5 µm filter with aeration (Fig. 3-2A, 3-2B). A hydraulic loading limitation was not observed with the 10 µm filter with and without the third lagoon cell being aerated across the complete TSS loading range of 25.2-574.1 g-TSS/m2/h (Fig. 3-2**Fig. 3-2**B). The 10 µm filter showed that TSS loading was significantly correlated to the increase in backwash frequency ($\mathrm{r} = 0.706$; $p < 0.001$)(Fig. 2B). The impact of individual parameters on backwash frequency was assessed with a comparison of normalized coefficients from a multiple regression model (R-squared=76.61%). This analysis demonstrated hydraulic loading (normalized coefficient = 7.52, p <0.001) and influent TSS (normalized coefficient = 9.99, p <0.001) as similarly weighted predictors of backwash frequency. Although both constituting parameters of TSS loading (influent TSS concentration and hydraulic loading) were significant predictors to an increase in backwash frequency on the 10 µm filter ($p < 0.001$), neither of these parameters caused a hydraulic load limitation to be observed on the 10 µm filter for TSS loadings applied in this study.



A

B

Fig. 3-2. Hydraluic loading rate across TSS loading rate, A) targeted (dotted lines) and actual (symbols) hydraulic loading rates versus solids loading rate, B) backwash frequency versus solids loading rate

The 5 µm filter experienced constant backwash at the observed elevated hydraulic loadings above 6.85m/h while operating at solid loading rates of 53.2 - 269.3 g-TSS/m2/h (Fig. 3-2B). This operational condition was induced exclusively by hydraulic loading as the impact of influent solids concentration was insignificant. This is supported by the weak correlation between TSS loading and backwash frequency (r=0.251, p=0.384) (Fig. 3-2**Fig. 3-2**B) along with influent TSS concentrations and backwash frequency(r=-0.366, p=0.195). This is also supported by the strong correlation between hydraulic loading and backwash frequency (r=0.997, p<0.001) (Fig. 3-2A, 3-

2B). Additionally, the comparison of normalized coefficients of a multiple regression model (R-squared=99.71%) comparing the impact of influent TSS concentration and hydraulic loading and backwash frequency highlighted hydraulic loading (normalized coefficient = 34.79, p <0.001) as the principal predictor compared to Influent TSS (normalized coefficient = -2.199, p =0.009). Therefore, the TSS concentration was not a principal predictor of backwash frequency for the 5 µm filter data. This is due in part to the hydraulic load limitation and overflow condition of this filter as hydraulic overloading induces excessive backwashing which increases the energy consumption of the system and limits hydraulic flexibility. Therefore, the effect of hydraulic loading on the system reduces the intrinsic technological advantages of microsieves over high headloss membrane systems such as micro-filtration. Filtration performance is not inhibited by backwater conditions as this does not affect solids removal performance directly, but is detrimental to the process effectiveness and requires consideration in design (Persson et al., 2006; Langer et al., 2017). The hydraulic load limitation of the 5 µm filter at loading rates above 6.85 m/h highlights a stricter hydraulic design constraint in comparison with the 10 µm filter. Since the solids concentrations in lagoons are typically within similar ranges for well-performing systems (effluent TSS concentrations of 10 – 40 mg-TSS/L), the principal implication of these findings is that the hydraulic capacity of filters with smaller pore sizing should be considered a principal design factor, in respect to hydraulic operating conditions without the use of coagulants or flocculants.

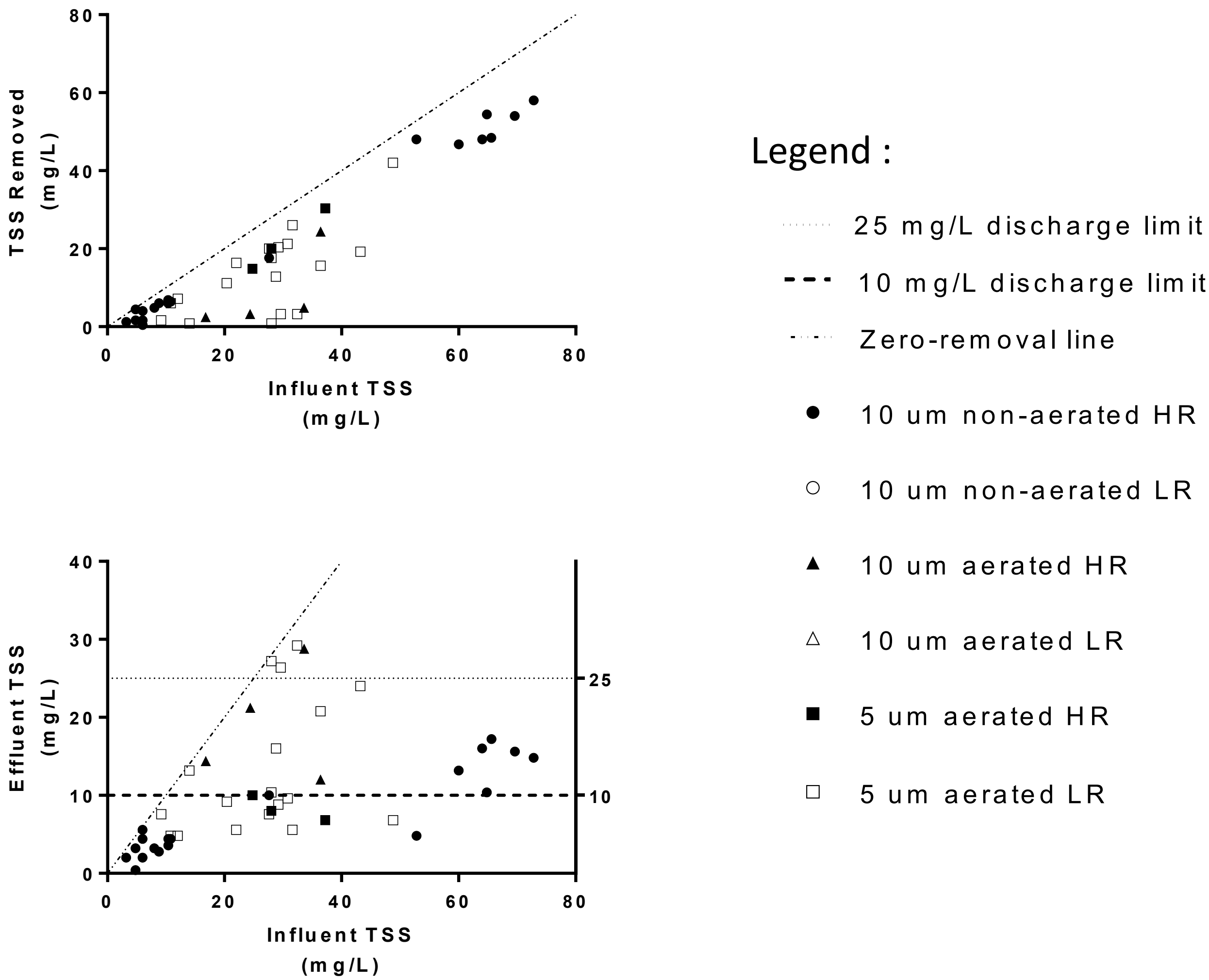
3.4.3 Solids removal performance

The solids removal performance of the 10 µm filter was evaluated across TSS loadings while being fed from the maturation lagoon cell that was either not aerated or aerated. While the maturation pond was not aerated, the TSS removal of the 10 µm filter was on average 60.1±22.6%, ranging from 6.7% to 91.78% across TSS loadings of 25.2 to 574.1 g-TSS/m2/h (Table 3-3). A significant difference in the TSS removal performance of the 10 µm filter was observed when the third lagoon cell was aerated compared to when the cell was not aerated ($p < 0.001$). Although the 10 µm filter showed good removal performance without aeration of the third lagoon cell, the deterioration of TSS removal during aeration was substantial, at which point the 10 µm filter was no longer capable of performing statistically significant removal of the TSS. This reduction in removal efficiency occurs across TSS concentrations of 14.0 to 36.4 mg/L and notably across a lower range of TSS loadings of 80.0 - 313.7 g-TSS/m2/h compared to the 10 µm filter in non-aerated conditions (Fig. 3-3A). The deteriorated performance of the filter that coincided with the use of aerators in the third lagoon cell was likely due to the aerators promoting the resuspension of smaller settled particles from the lagoon benthic zone, which are poorly removed by the 10 µm filter.

Table 3-3. TSS removal efficiency of the filters

Filter	Mean Removal (%)	Range of Removal (%)	Removal Significance	*p* -value
10 µm non-aerated	60.1±22.6	6.7 - 91.7	Yes	0.029
10 µm aerated	17.2±20.5	2.7 - 67.0	No	0.256
5 µm aerated	68.2±9.8	54.9 - 82.3	Yes	<0.001

While the 10 µm filter demonstrated poor solids removal performance during aeration of the third cell, the 5 µm filter demonstrated an average solids removal efficiency of 68.2±9.85%, ranging from 54.9% to 82.3% across the range of loadings of 53.2 to 269.3 g-TSS/m2/h and TSS concentrations of 7.6 to 37.2 mg/L (Fig. 3-3B). The 5 µm filter therefore demonstrated a significant improvement in solids removal as compared to the 10 µm filter while the third lagoon cell was aerated. This observation supports the likelihood of aeration in the third lagoon cell resuspending smaller particles, which were removed by the finer filter. Based on this observation, the size of the resuspended particles is likely to be in the 5 – 10 µm range. Regarding the impact of hydraulic loading on solids removal performance, there was no significant correlation observed between hydraulic loading and TSS removal efficiency for both filters.



A

B

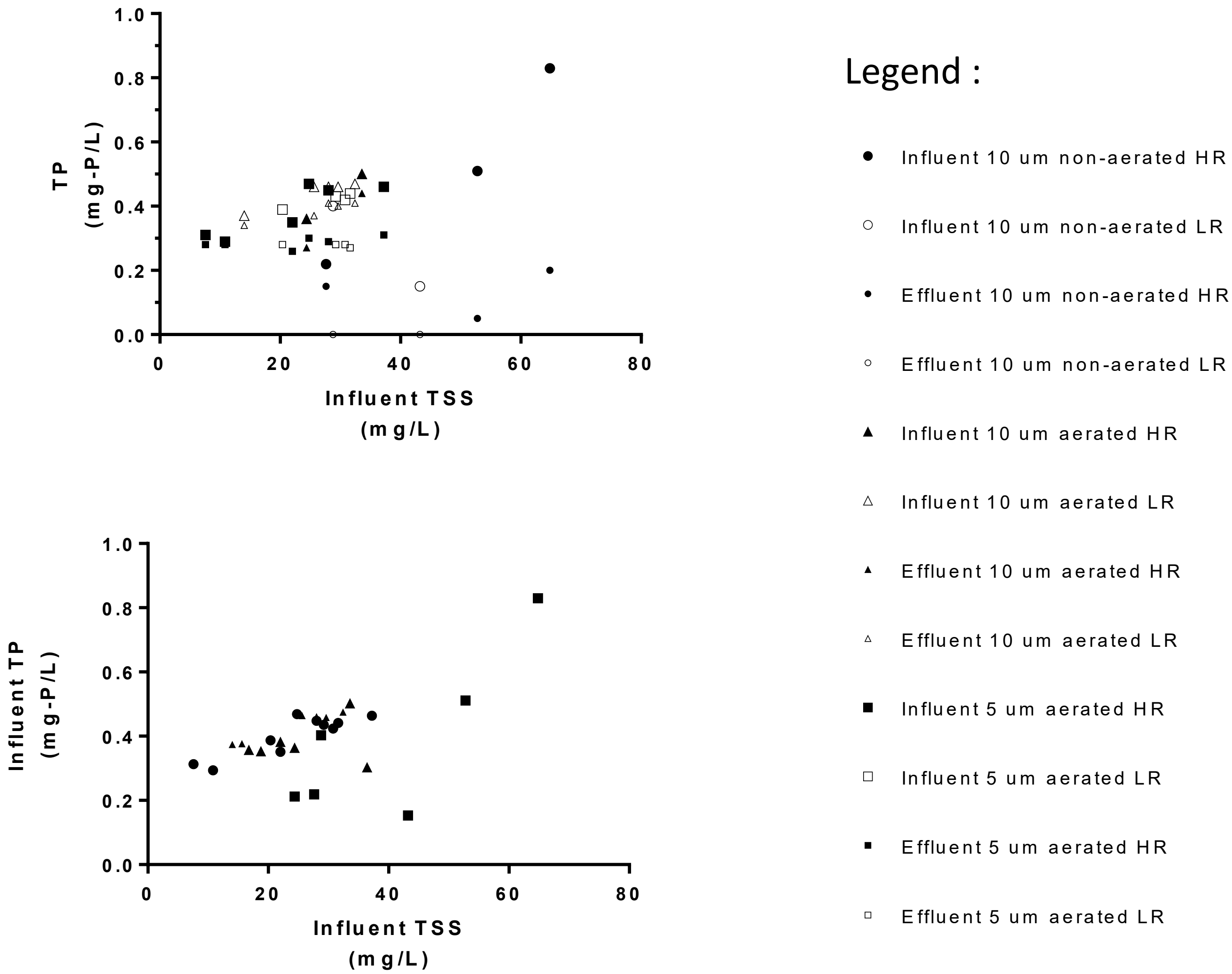
Fig. 3-3. TSS removal versus influent TSS concentration, A) TSS removed (symbols) vs. theoretical 100% removal (inclined dotted line), B) TSS effluent (symbols) vs. theoretical 100% removal (inclined dotted line), effluent criteria (horizontal dashed line)

The effluent TSS is an important metric to evaluate if the filters are capable of providing the effluent quality required to meet typical design targets (10 mg-TSS/L) and typical effluent regulation (25 mg-TSS/L) (Mavinic et al., 2018b) (Fig. 3-3). The 5 µm filter demonstrated robust solids removal and enhanced effluent quality compared to the 10 µm , both with and without aeration in the third lagoon cell. The 10 µm filter was not able to meet typical discharge regulation of 25 mg-TSS/L for 80% of the data points under aerated lagoon conditions. In contrast, the 5 µm filter demonstrated an ability to meet design targets of 10 mg-TSS/L for all data points measured. Therefore the 5 µm filter provided more robust lagoon solids removal compared to the 10 µm filter. These findings support the theory that fine particle characteristics changed in the lagoon during aeration of the third cell. It should be mentioned that the addition of a coagulant, flocculant, and/or polymer at the filter unit with the 10 µm filter may increase the TSS removal and the produce effluent TSS concentrations at the target value. The advantage of this solution would be the preservation of hydraulic flexibility/capacity provided by the 10 µm filter, while potentially reducing effluent TSS concentrations to target values.

3.4.4 Discfilter peripheral benefits of TP and chlorophyll α removal

TP influent concentrations to the filter unit ranged from 0.15 to 0.83 mg-P/L with concurrent solids loadings of 25.1 – 574.1 g TSS/m2/h (Fig. 3-4A). It should be noted that the average influent TP concentrations of 0.4 ± 0.13 mg-P/L observed in this study falls in the lower range of TP concentrations measured in lagoons, and of those found in other studies on the discfilter (applied to mechanized wastewater treatment plants) focusing on phosphorus removal with and without coagulants or flocculants (Bourgeous et al., 2003; Tooker et al., 2012; Wilén et al., 2012; Kängsepp et al., 2016; Langer et al., 2017). The lagoon effluent TP concentrations were low in concentration due to an alum dosing for phosphorus control in the influent of the lagoon facility. The 10 µm filter provided significant TP removal during the non-aerated condition of the lagoon ($p = 0.029$) with average removal of 80.0±28.2% or 0.34±0.23 mg-P/L. Conversely, TP removal was not significant by the 10 µm filter operated during aeration of the third lagoon cell ($p = 0.256$) (Table 3-4). The 5 µm filter provided an average removal of 32.7±18.2% or 0.12±0.06 mg-P/L and demonstrated significant TP removal ($p < 0.001$) in aerated conditions.

Soluble phosphorus compounds did not show significant removal with respect to either the 10 µm or 5 µm filters. Higher TP removal is observed in this study for the 10 µm filter under non-aerated third lagoon cell conditions and also under the aerated third cell conditions (Fig. 3-4A). In addition, higher TP removal is again observed in this study for the 5 µm filter conditions under aerated third lagoon cell conditions at elevated TSS concentrations (Fig. 3-4A). Statistical analysis indicates that influent TP concentrations were on a moderate upward trend when influent TSS concentrations increased (r=0.569, $p = 0.050$).



A

B

Fig. 3-4. Phosphorus removal vs. influent TSS, A) influent and effluent TP concentrations, B) TP/TSS fraction; all datasets confounded

Table 3-4. TP removal performance of the filters

Filter	Mean Removal (%)	Mean Removal (mg/L)	Removal Significance	*p* -value
10 µm non-aerated	80.0±28.2	0.35±0.23	Yes	0.029
10 µm aerated	5.3±18.0	0.03±0.07	No	0.256
5 µm aerated	32.7±18.2	0..11±0.06	Yes	< 0.001

The removal of chlorophyll α (Chl. α) was determined for both the 10 µm and the 5 µm filters, with influent Chl. α ranging from 4.1 to 23.4 µg- Chl. α/L across the study (Fig. 3-5, Table 3-5). Typically facultative lagoons have Chl. α concentrations that can range from 500 to 2000 µg-Chl. α/L, while maturation ponds have reported levels of 200 to 500 µg-Chl. α/L (Buisine and Oemcke, 2001; Mara, 2004). Therefore the Chl. α concentrations of this study are low compared to typical values.

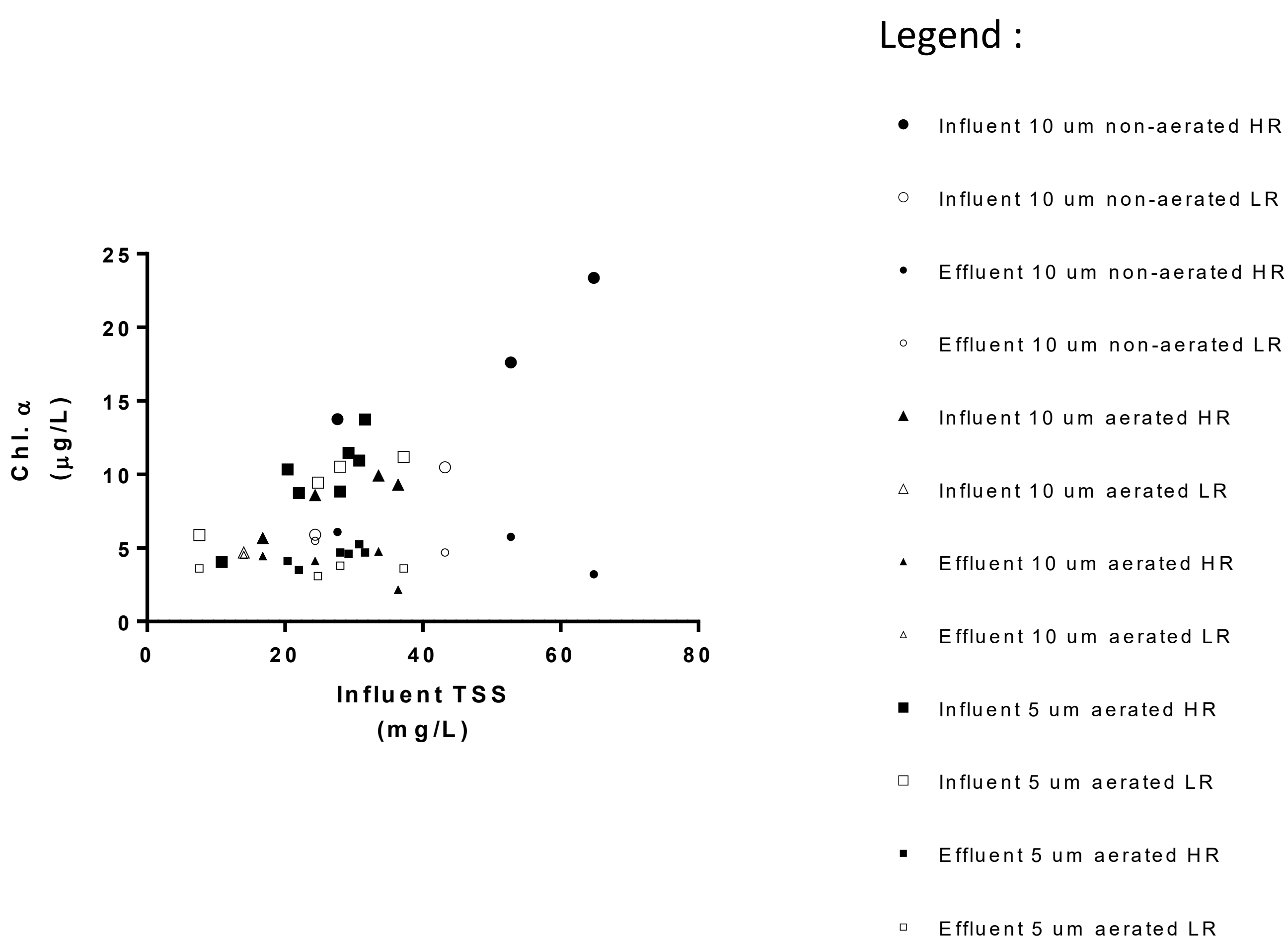


Fig. 3-5. Influent and effluent chl. α concentration versus Influent TSS concentration

Table 3-5. Chl. α removal performance of the filters

Filter	Mean Removal (%)	Mean Removal (μg/L)	Removal Significance	p -value
10 μm non-aerated	66.1±14.5	11.4±6.4	Yes	0.05
10 μm aerated	41.2±28.7	3.6±2.9	Yes	0.048
5 μm aerated	58.2±9.5	6.0±1.9	Yes	<0.001

The 10 μm filter showed significant removal in both the non-aerated condition ($p = 0.050$) and aerated conditions ($p = 0.048$); with an average effluent concentration of 5.2±1.28 μg-Chl. α/L and 4.0±1.0 μg-Chl. α/L, respectively. The 5 μm filter also demonstrated significant removal ($p < 0.001$) with an average effluent concentration of 4.1±0.65 μg-Chl. α/L. As such, the removal of Chl. α was effective in this study using both filters at all conditions that maintained a steady and low effluent Chl. α concentration across the applied TSS loading range. In this study, Chl. α of the lagoon effluent across all conditions of the two filters was correlated with influent TSS ($r = 0.859, p < 0.001$), and followed a linear trend with an R-squared value of 72.82% (Equation 2).

$$(\boldsymbol{Influent\ Chl.\alpha})\left[\frac{\boldsymbol{\mu g}}{\boldsymbol{L}}\right] = \mathbf{1.72 \pm 1.26 + 0.2893 \pm 0.039} * (\boldsymbol{Influent\ TSS})\left[\frac{\boldsymbol{mg}}{\boldsymbol{L}}\right]; \boldsymbol{R^2} = \mathbf{72.82\%}\ (\boldsymbol{Eqn.2})$$

Microscopy was performed on the backwash water of the 10 and 5 μm filters across all conditions to identify the prevalent algae species being removed by the discfilter from the lagoon effluent. Microscopy confirmed removal of the following species of algae from the lagoon: Wilmottia, Desmodesmus, Chrolumina, Cynura, and Phacus. These species have been observed in previous studies in lagoon wastewaters (Buisine and Oemcke, 2001; Pearson, 2003).

Although this study sampled solids directly from the effluent of a real lagoon system, the samples collected were subject to changing site conditions due to the pilot nature of the study. The principal advantage of experiments on the pilot-scale is the accurate representation of real conditions. These advantages are tied to the inherent difficulties of pilot work such as limited control over individual variables, and the increased difficulty of sample collection and analysis. Additional research is required to better understand the overall characterization of solids and characteristic changes with respect to time, aeration, algae growth, and temperature within lagoon systems in general.

3.5 Conclusions

With respect to hydraulic performance, the 10 µm filter was able to convey the imposed flowrates across the complete applied range of hydraulic loadings of 4.72 to 9.34, whereas the 5 µm filter demonstrated a limited flow conveyance capacity at elevated hydraulic loadings of 6.85 m/h and above. The operation of aerators in the third cell of the lagoon system limited the solids separation efficiency of the 10 µm filter, likely due to entrainment of smaller sized benthic solids into the lagoon effluent. The 5 µm filter was able to provide robust solids separation efficiency during aeration of the third lagoon cell that met typical target effluent TSS concentrations. TP removal as a peripheral benefit of the discfilter operation was significant for the 10 µm non-aerated condition and 5 µm filter aerated condition, hence following the trends observed with TSS removal performance. Algal removal performance through the removal of Chl. α was effective using both filters at all conditions with steady, low effluent concentrations being maintained across the applied TSS loading range. Overall, this study demonstrates the potential of the discfilter technology for enhanced solids removal in lagoons to improve compliance with strict effluent discharge requirements.

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4 Synthesis and conclusions

4.1 Conclusions of study

A principal challenge to wastewater treatment in rural communities is the prevalence of passive wastewater treatment systems that are susceptible to non-compliance of wastewater effluent regulations. Furthermore, effluent discharge regulations affecting wastewater treatment facilities are becoming increasingly stringent. Mechanized wastewater treatment technologies that are able to generate effluent that complies with stringent regulations require significant infrastructure and operational expenses compared to passive treatment technologies.

Rural communities often do not readily have access to existing infrastructure to support mechanized technologies and, because of their size, may not have the financial capacity to support the added operational and maintenance expenses, qualified personnel, and fixed costs associated with such systems. Additionally, these communities typically do not generate the volume of wastewater required to make these investments economically beneficial. This limits the economic viability of mechanized wastewater treatment technologies in rural communities, where the financial investment allocated to wastewater treatment risks becoming too important. A more effective and efficient solution, if achievable, would be to upgrade the existing passive treatment technologies to guarantee compliance with the stringent regulations on wastewater contaminants released.

Regarding compliance with suspended solids regulations, passive treatment systems such as lagoons, have been shown to be plagued by non-compliance of effluent suspended solids. This is typically caused by changes in the characterization, settling characteristics, and therefore removal efficiency of solids in these systems across their lifespan and also across periods of solids removal and dredging from the lagoons. Solids are therefore an unpredictable wastewater treatment parameter in lagoons, with lagoons being one of the most prevalent technology for passive wastewater treatment in Canada for rural communities.

The discfilter technology is compatible and complementary to many rural lagoon wastewater treatment facilities. Discfilters are not operationally intensive systems and can perform under low flow conditions with low energy consumption, while having the advantage of a modular system with low footprint and land use requirements. Although the discfilter technology has the potential to be compatible with lagoon systems, their performance benefits have only been demonstrated in mechanical system applications on primary, secondary and tertiary wastewater streams and has yet to be studied and demonstrated in lagoon applications.

The objective of this study is to evaluate the discfilter technology as a potential upgrade technology for the improvement of passive wastewater systems such as lagoon with respect to effluent suspended solids compliance. A pilot scale Hydrotech® discfilter was tested with respect to typical discharge conditions and changing lagoon conditions. To achieve this objective, two filter cloth materials were studied to demonstrate the discfilter technology in a lagoon application. This principal objective was met and the study demonstrated the performance of two filter materials in operation of the discfilter system, with analysis in performance hydraulic load limitations and effectiveness of solids removal. The findings from this pilot-scale experimental work were the following:

- The 10 µm filter demonstrated effluent total suspended solids (TSS) concentrations less than 25 mg-TSS/L during non-aerated operation of the final lagoon cell, with a higher hydraulic capacity compared to the 5 µm filter.
- The 10 µm filter showed susceptibility to changes in solids characteristics during aeration of the final lagoon cell, with 80% of non-compliant influent exceeding effluent TSS concentrations of 25 mg-TSS/L.
- The 5 µm filter showed resilient removal across all lagoon conditions, including aeration of the final lagoon cell.
- The 5 µm filter was limited to a hydraulic loading of 6.85±0.03 m/h in this study.
- Total phosphorus was shown to be removed to levels at or below 0.3 mg-P/L from influent concentrations of 0.15 to 0.8 mg-P/L and algae/Chlorophyll α was shown to be removed to levels below 7 µg-Chl. α/L for concentrations ranging from 4 to 24 µg-Chl.α/L.

The findings of this study demonstrate that the performance of the discfilter technology observed when applied to mechanical treatment systems are also observed in its application to lagoons. The findings also highlight that the solids characteristics and the dynamics of these solids in lagoons requires further understanding. In relation with the discfilter operation, lagoon solids dynamics can have a significant impact on performance.

4.2 Implementation and impact of study on first installation of discfilter technology to lagoons in Canada

Implementation of this technology requires understanding of the global issues facing lagoons. The performance gaps of lagoon systems are not limited to solids removal but also include the limited nutrient removal and specifically limited nitrification in temperate climates due to cold temperatures. Therefore, discfilter systems can be coupled with additional upgrade solutions to solve the existing issues of lagoon facilities. Specifically, the discfilter can also be implemented in succession with biological treatment upgrade units. Biological units such as the moving bed biofilm reactor (MBBR) attached growth system have recently been shown to enhance nitrification in lagoon systems, which may present solids production issues that require post-nitrification treatment separation. The discfilter may also be compatible within this context. Notably, the lagoon studied in this study is undergoing design for upgrading to post-lagoon nitrification followed by the discfilter technology. Hence, although this study was performed on the removal of effluent solids directly from the lagoon facility, the data collected from this pilot study was used to design the first full-scale installation of the discfilter treating effluent from the lagoon facility that is to be first treated by a post-lagoon, nitrifying MBBR unit and subsequently treated by the discfilter unit.

4.3 Application of study data to design of discfilter system for solids removal at a lagoon facility

A hypothetical design was prepared as part of this work to illustrate how the findings of this study may be directly applied to the design of the discfilter system for solids removal from the lagoon effluent. This hypothetical case is based on the existing regulations and operation procedures of the lagoon facility of this study. In particular, the design of the discfilter unit to directly treat the effluent from the lagoon facility researched in this study. The components of design of the discfilter revolve principally around the hydraulic load and the target effluent solids concentration, both being equally important. Additionally, the existing environmental compliance agreement (Ministry of the Environment Conservation and Parks, 2018) of this facility was used as a basis for the regulated performance criteria in this design.

This hypothetical design is made under the assumption that there are no additional changes to the lagoon configuration or operations besides the installation of a discfilter unit. The hypothetical design assumes that the system would comply with the current environmental compliance agreement (Ministry of the Environment Conservation and Parks, 2018) and permissible discharge parameters, as well as flowrates that consider appropriate population growth. The performance targets for this hypothetical design are to meet the design objectives for the lagoon system. This involves producing an effluent with a TSS concentration below 10 mg/L without chemical enhancement, from an influent TSS concentration of 20 to 40 mg/L. As for the target hydraulic loading, the target performance is set to meet the allowed discharge volume at an economical size considering downtime requirement. A backwash frequency of 25% is targeted to maintain reasonable energy consumption of the system.

Based on the observed performance of the lagoon and the results of our pilot study on this system, the 5 µm filter is selected in our hypothetical design due to its ability to meet the current design objectives of the system, during normal discharge operations. Secondly, the discharge requirement is the key parameter that impacts the sizing of the unit within a range of allowable hydraulic loadings for the filter material. Further considerations include the minimum allowable discharge capacity which is governed by the permissible discharge volume of the facility, maximum flowrate and discharge period again governed by the permitted discharge period of the facility, as well as provisions for downtime and flexibility in flow control that exists within the current infrastructure.

For the determination of the design flowrate, permissible discharge volumes and durations per season from existing permitting documents were considered for the assessment of minimum allowable flowrates (Table 4-1). The effluent flowrate in this hypothetical design does not account for water losses within the lagoon itself. To account for downtime of the filter, the operating flowrate was multiplied by a design factor to evacuate the same volume of water within a constrained discharge period. For this assessment, taking the highest seasonal average flowrate with a design factor of 1.785, the resulting design operating flowrate corresponds to 13 000 m^3/d, which allows for a conservative 30 days of downtime during the most constrained discharge period. Increased flow control and flow equalization allows for more constant discharge rates, and an effluent flowrate that is unaffected by peaking flowrate. The consideration with respect to flow control is an important distinction in selecting a design flowrate for a lagoon WRRF compared to a mechanized WRRF. This is due to the capacity of lagoons to equalize flow, allowing a relatively constant discharge rate. In mechanized WRRFs, minimum allowable flowrate is governed by the peak flowrates (i.e. peak hour) in the WRRFs due to these plants having less flow equalization capacity.

Table 4-1. Design flowrate determination for the Casselman lagoon

Parameter	Value	Units
Average Lagoon Inflow Rate	2 110	m^3/d
Lagoon Influent Volume	770 150	m^3
Peak Allowable Effluent Flowrate	18 600	m^3/d
Allowable Discharge Volume Spring	502 500	m^3
Discharge Duration Spring	69	days
Allow. Discharge Volume Fall	267 650	m^3
Discharge Duration	79	days
Average Discharge Spring	7 283.0	m^3/d
Average Discharge Fall	3 388.0	m^3/d
Min. Design Discharge Rate	7 283.0	m^3/d
Design Factor	1.785	unitless
Design Discharge Rate	13 000	m^3/d
Design Discharge Duration (Spring)	38.65	days
Downtime (Spring)	30.35	days

Although lagoons benefit from flow equalization, the volume of discharge in a short period require a much larger flowrate than a mechanical system of the same size. For example, if using a peak hour factor of 3.8 (Brière, 2014) and identical average inflows, the design would yield a design flowrate of 8 018 m^3/d, which is within 11% of the minimum design discharge rate (7 283 m^3/d) for the lagoon-based system. Therefore, the design must consider the lagoon discharge configuration (continuous vs. seasonal) and duration. The permissible discharge volumes and peak discharge rates stipulated by lagoon regulations are constrained in this case by other effluent quality parameters and regulations of the lagoon and receiving waters (i.e. ammonia, carbonaceous biological oxygen demand, phosphorus, pathogens, etc.). In this case specifically, the lagoon discharge period is limited by winter effluent ammonia concentrations.

The filter was sized to meet the target backwash frequency and therefore, a hydraulic loading of 4 m/h was selected from the performance data of this study. This resulted in a filter area requirement of 135.5 m^2, based on the selected design flowrate. Using a standard disc diameter of 2.2 m with an effective area factor of 0.65 per disc to consider for the partial submergence of the discs and the area contributing to filtration, an estimated total of 55 discs are required to provide this filtration area (Table 4-2).

Table 4-2. Discfilter sizing for the lagoon system at Casselman

Parameter	Value	Units
Design Flowrate	13 000	m^3/d
Allowable Hydraulic Loading	4.0	m/h
Area Required	135.5	m^2
Disc Diameter	2.2	m
Area/disc	3.8	m^2
Effective Area Factor	0.65	unitless
Disc Total	55	units
Total Area Provided	135.9	m^2
Solids loading Rate	80-160	g TSS/ m^2/d

For the satisfaction of the HGL requirements, the site conditions, available freeboard between the lagoon and point of discharge, and the evacuation of waste backwash water and solids to the primary lagoon cell should all be considered when determining pumping requirements and configuration of the HGL profile through the system. In addition to the principal design parameters discussed above, the design must also consider the incorporation of bypass capacity and other emergency and safety systems to ensure enhanced reliability of the system. The determination of this capacity and the design of safety systems is beyond the scope of this hypothetical design. Overall the hypothetical design described above highlights the main considerations for design and demonstrates the implications of the findings in designing this technology for lagoon effluent TSS tertiary treatment.

4.4 Recommendations for future work

Based on the findings raised in this study, the following recommendations are provided for further research to fully understand the performance of the discfilter system applied to lagoon facilities:

- Supplementing the TSS removal performance of the discfilter with coagulation and flocculation.
- Assessing the discfilter performance at other lagoon facilities with different lagoon types and configurations, including aerated lagoons, facultative lagoons without maturation ponds, in continuous flow configurations.
- Assessing the discfilter performance with respect to higher algae concentrations and differing solids characteristics
- Assessing the discfilter performance following compatible and appropriate biological cold-temperature nitrification technologies.

4.5 References

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