A Combined Reed Bed / Freezing Bed Technology for Septage Treatment and Reuse in Cold Climate Regions

Kinsley, C.[1,2], Kennedy, K.[2], Crolla, A.[1]

[1]Ontario Rural Wastewater Centre, Université de Guelph – Campus d'Alfred, 31 St. Paul St., Alfred, Ontario, Canada, K0B1A0
[2]University of Ottawa, Department of Civil Engineering, 161 Louis Pasteur, Ottawa, Ontario, Canada, K1N 6N5 (ckinsley@uottawa.ca)

Abstract
A combined reed bed-freezing bed technology was effective at treating septage under Canadian climatic conditions over a 5 year period with average loading rates of 82-104 kg TS/m^2/y. Varying hydraulic and solid loading rates as well as the increasing sludge cake with time had little to no effect on treatment efficiency with almost complete removal of organic matter, solids, heavy metals and nutrients. Filtrate concentrations varied significantly between the freeze-thaw and growing seasons for many parameters, although the differences were not important from a treatment or reuse perspective with filtrate quality similar to a low to medium strength domestic wastewater. The potential to reuse the filtrate as a source of irrigation water will depend upon local regulations. The dewatered sludge cake consistently met biosolids land application standards in terms of pathogen and metals content, with *E.coli* numbers declining with time as sludge cake depth increased. A combined reed bed – freezing bed technology can provide a cost-effective solution for septage management in northern rural communities with potential for beneficial reuse of both the filtrate and dewatered sludge cake.

Keywords: septage, reed bed, freezing bed, metals, pathogens, agricultural reuse

INTRODUCTION

Septage, the solids accumulated in septic tanks, has traditionally been applied to agricultural land without treatment in Ontario (Canada). However, public policy is moving towards regulating septage as a biosolid with pathogen and metals limits; as is the case in many jurisdictions throughout North America (CCME, 2010; USEPA, 1994a). Disposal of septage at municipal treatment plants is often not feasible, as town wastewater systems, which are often lagoons, are generally not equipped to receive and treat septage. A low-cost technology which can dewater and treat septage year-round and be able to meet biosolids reuse standards is needed for rural communities in cold-climate regions such as Ontario. It is hypothesised that a combined reed bed and freezing bed technology can meet these requirements.

Reed bed filters are similar in design to conventional sand drying beds only planted with common reeds (*Phragmites*). The main difference between a reed bed and a sand drying bed is that the sludge is left to accumulate in a reed bed over a period of 6-10 years, greatly reducing operating costs. The reeds play two important roles: firstly, the growing rhizomes and movement of the stems in the wind break apart the accumulating sludge layer and permit continuous filter drainage and secondly, plant evapotranspiration increases sludge dewatering (De Maeseneer, 1997). Reed beds have been used extensively in Europe for dewatering municipal waste activated sludges (WAS) and mixed WAS and anaerobic digestion (AD) sludges with recommended loading rates of 60 and 50 kg total solids (TS)/m^2/yr, respectively (Nielsen, 2003). As well, a limited number of studies have shown reed beds to be effective at septage dewatering: two full scale systems in France at loading rates of 46 and 109 kg TS m^2/y (Paing and Voisin, 2005), and pilot system in France at 50 kg

TS/m^2/y (Vincent et al., 2011) and two pilot systems in tropical countries at much higher loading rates of 250 kg TS m^2/yr (Koottatep *et al*, 2005) and 100-300 kg TS m^2/y (Kengne *et al*, 2009). However, the reed bed technology has not been adapted to operate under freezing conditions.

It is hypothesised that reed bed filters can be operated as freezing bed filters during the winter months. Martel (1993) conducted pioneering work with freezing beds and proposed a design for a freezing bed filter consisting of a sand drying bed with extended side walls to accommodate the accumulating layers of sludge applied and frozen during the winter, with dewatering occurring in the spring. As sludge freezes, particulate matter is rejected during ice crystal formation and consolidated into solid particles along the crystal boundary, greatly increasing dewaterability (Reed *et al*, 1986). Freezing beds have been successfully operated at the pilot scale in the N.E. United States to treat WAS, AD sludge and water treatment plant alum sludge (Martel and Diener, 1991; Martel, 1993) and in Ontario, Canada to treat septage (Kinsley et al, 2012).

This study explores the application of a combined reed bed / freezing bed (RB-FB) technology to treat and dewater septage and focusses on the effect of operating conditions (loading rate, operating season, accumulating sludge cake with time) on filtrate and sludge cake quality for reuse applications. Figure 1 depicts potential reuse and disposal options for RB-FB by-products.

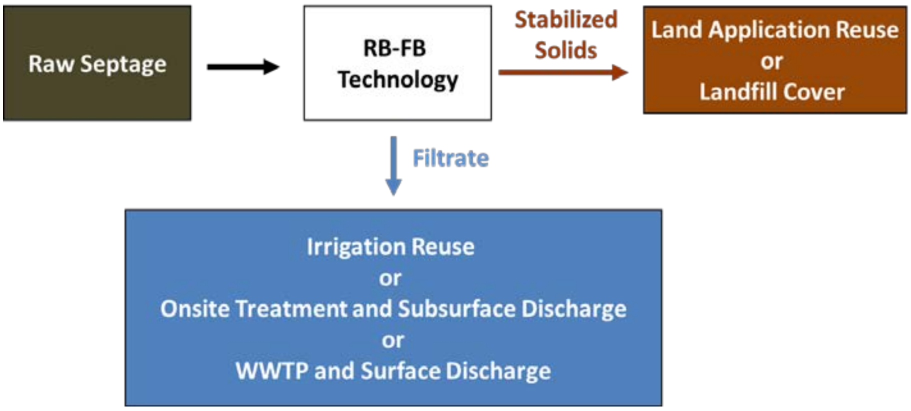

Figure 1. Reuse and disposal options for solid and liquid streams from septage treated in a reed bed - freezing bed technology.

The potential for reuse of the sludge cake will typically be governed by biosolids regulations with limits on heavy metals and pathogens (CCME, 2010). Nutrient (N:P:K) and organic matter (OM) content are the key economic drivers for beneficial reuse as the dewatered sludge cake can substitute manure, compost or organic soil applied to agricultural land, parkland or land reclamation sites (USEPA, 1994b). Most jurisdictions specify one threshold for unrestricted reuse with very low metal concentrations and non-detect pathogen numbers as well as a second threshold for restricted reuse with higher metal concentrations and moderate pathogen numbers (typically 2.0 x 10^6 *E.coli* / g dry matter (d.m.)) (Iranpour et al., 2004). The potential for reuse of the filtrate for irrigation purposes will depend upon wastewater reuse guidelines or regulations, and will typically include limits on pathogens, salinity, biochemical oxygen demand (BOD), total suspended solids (TSS) and toxic metals (USEPA, 2012; WHO, 2006; Alberta Environment, 2000).

MATERIALS AND METHODS

Two reed bed systems (RB1 and RB2) and one non-planted sand filter (SF) were constructed at the septage lagoon of René Goulet Septic Tank Pumping, Green Valley, ON, Canada (45.32°N 74.64°W). The study site is located between Ottawa, ON and Montreal, QC. Average monthly 25-year temperature climate normals vary from -10.8°C in January to 20.9°C in July, with average temperatures remaining below the freezing point from December through March.

Each filter is 187 m^2 and was sized to receive individual loads of 13.6 m^3 from a septage vacuum truck; which represents a 7.3 cm dose, and is slightly lower than the 8.0 cm dose recommended by Martel (1993) for freezing bed operation. The filter design was based upon recommended specifications for sand drying beds (Wang et al., 2007). A cross sectional schematic and photo of the system is presented in Figure 2. Details of the design and construction can be found in Kinsley (2016). The systems were dosed directly from the vacuum truck onto a splash plate after passing through a 1.0 cm bar screen to remove large non-biodegradable objects. Filtrate was pumped to an existing lagoon and used to irrigate poplar plantations during the summer months.

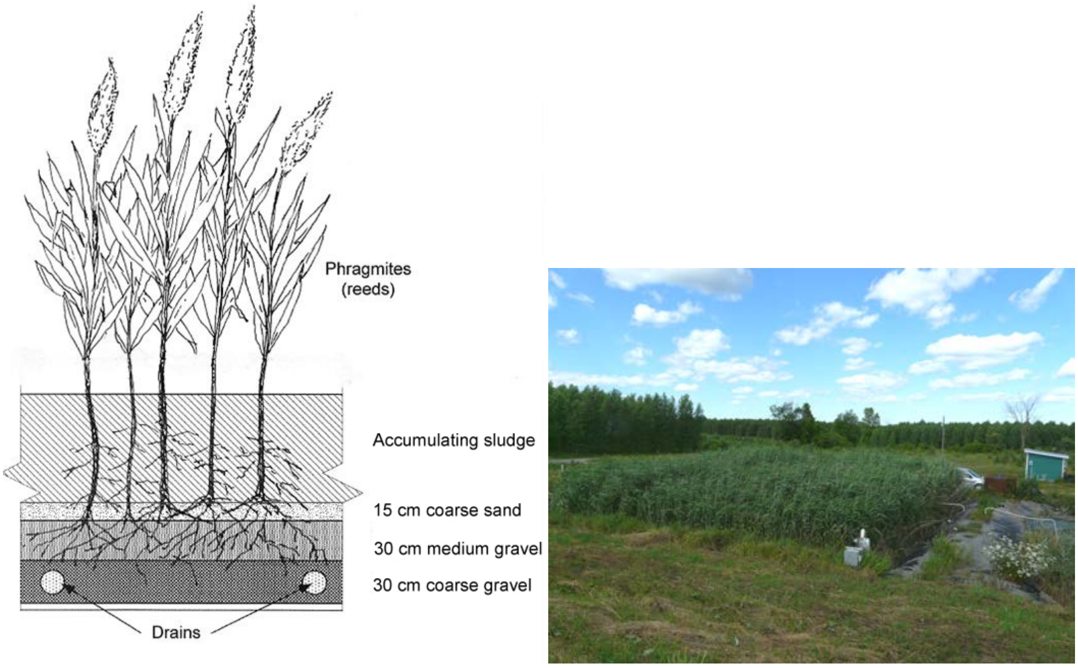

Figure 2. Pilot Reed Bed – Freezing Bed System Schematic and Photo with Poplar Plantation in Background

The systems were operated as reed beds from May to November with scheduled dosing and as freezing beds during the winter months, where a new dose of septage was applied once the previous dose had frozen. Over the course of the five year study both hydraulic loading rate (HLR) and solid loading rate (SLR) were varied widely to compare operating conditions on dewatering efficiency (see Table 1) and is presented elsewhere (Kinsley, 2016). Solid loading rates to the filters ranged from 43 to 147 $kg/m^2/yr$, with average loading between 82 – 104 $kg/m^2/yr$; which is consistent with the loading rates reported by and Paing and Voisin (2006) but is considerably higher than the 50-60 kg/m^2/yr recommended by Nielson (2003) for WAS and WAS mixed with AD sludge.

Table 1. Annual solid and hydraulic loading rates to systems by calendar year

Year	SF		RB1		RB2	
	SLR (kg m^{-2} y^{-1})	HLR (m y^{-1})	SLR (kg m^{-2} y^{-1})	HLR (m y^{-1})	SLR (kg m^{-2} y^{-1})	HLR (m y^{-1})
2007	142	3.2	144	3.3	113	3.4
2008	91	2.4	75	2.8	49	2.8
2009	88	3.6	91	3.1	74	3.4
2010	147	5.9	43	1.9	81	3.5
2011	54	2.4	58	2.6	110	4.6
Avg.	104	3.5	82	2.7	85	3.5

Representative 2 L septage samples were collected from each truck load and stored in a sample fridge located on site. A peristaltic pump activated by the effluent pump in each pump chamber collected flow-proportional composite filtrate samples with filtrate samples collected on a bi-weekly basis. Grab samples were collected for bacteria analysis. Sludge cake samples consisted of a composite of 4 cores within each bed collected using a 5 cm dia. soil corer. Raw septage and filtrate samples were analysed for a common suite of water quality parameters (COD, BOD, TS, VS, TSS, TKN, NO_3^-, TP, *E.coli*) at the Ontario Rural Wastewater Centre environmental quality laboratory following Standard Methods (APHA, 2005) while metals analyses and sludge N, P, K were analysed at the Ontario Ministry of Environment laboratory following EPA methods (SCC, 2013).

Statistical design

Filtrate quality was compared between filters over the entire study period for each parameter using a single factor ANOVA. Where significance was found ($P<0.05$), a post hoc T-test assuming equal variance with Bonferroni correction was conducted (Dunn, 1961). To evaluate the effect of loading rate on filtrate concentration, a two-way ANOVA without replication was conducted for each year with sample date and filter as variables. If significance was found ($P<0.05$), a paired T-test with Bonferroni correction was conducted between each of the filter pairs. To compare the effects of operating period (Dec-April freeze-thaw vs May - November growing season) and time, a two-way ANOVA with replication was conducted. Blocked average data for each period was used with the three filters acting as replicates. All pathogen data was log normalized prior to conducting statistical analyses.

The effect of increasing sludge cake with time on *E.coli* numbers was compared using a two-way ANOVA without replication with filter and year as variables. As well, a correlation coefficient was determined between *E.coli* and sludge cake depth. Bacteria numbers between filters was compared using a two-way ANOVA with replication (3 sample depths) using filter and sample date as variables. Where significant was found ($P<0.05$), a post hoc T-test assuming equal variance with Bonferroni correction was conducted.

All statistical analyses were conducted using the Data Analysis Toolpack^{TM} in Microsoft Excel.

RESULTS AND DISCUSSION

Organic matter, solids and nutrients

The filters performed exceptionally well at removing organic matter, solids and nutrients from septage with average removal rates of 99% for COD, BOD_5 and TSS, 98% for TP, 90% for TN and 93% for TS (see Table 2). These results are very similar to those reported by Paing and Voisin (2005) at a full scale reed bed system treating septage in France and by Burgoon et al (1997) in a reed bed system treating lagoon biosolids in the Northwestern United States. The very high removal rates strongly suggest that the organic matter and nutrients are mostly related to particulate matter, which is removed through filtration. No significant differences in average filtrate concentration were observed between the three filters for COD, BOD and TSS ($P>0.1$), while TN filtrate concentrations were significantly higher in SF compared with both RB1 and RB2, and TP filtrate concentrations were significantly lower in RB1 compared with both SF and RB2 ($P<0.05$). These observed differences could be due to the fact that SF had the highest average SLR and HLR, while RB1 had the lowest in addition to the potential role of plant uptake. Filtrate TS was also significantly higher in SF, reflecting higher SLR to this filter over the course of the study. However, these differences are not relevant from a treatment perspective as the range of filtrate concentrations measured are typical of weak to average domestic wastewater (Metcalfe and Eddy, 2003), which can be discharged to the headworks of a municipal wastewater treatment plant or lagoon system, easily treated in any decentralised wastewater treatment system, or potentially used as a source of irrigation water.

Table 2. Septage Treatment in Sand Filter and Reed Bed Systems (Averages over 5 years)

Parameter	Raw Septage (Avg. ± SD) (mg/L)	Filtrate (Avg. ± SD)			Avg. Removal (%)
		SF (mg/L)	RB1 (mg/L)	RB2 (mg/L)	
COD	27,000±28,300	274±258	219±144	231±132	99.1
BOD_5	6,400±6,800	71±88	55±43	59±47	99.0
TS	25,800±24,000	*2310±800	1720±620	1750±600	92.5
TSS	19,500±18,400	114±155	79±80	102±97	99.5
TN (TKN + NO_3)	750±630	*91±43	67±31	65±28	90.0
TP	265±300	5.2±4.0	*3.8±2.5	5.4±2.8	98.2

* Significant difference at 95% confidence level using a single factor ANOVA with post hoc T-Test assuming equal variance with Bonferroni correction.

Wastewater reuse guidelines vary across jurisdictions; for example, Alberta Environment (2000) recommends CBOD and TSS < 100 mg/L while USEPA (2012) recommends secondary treatment with BOD and TSS < 30 mg/L in addition to pathogen limits. Reuse of the filtrate as a source of irrigation water will depend upon local regulations and may require further treatment depending upon the intended use.

To evaluate the effect of loading rate on filtrate quality, filtrate data was compared between filters for each year of the study. No significant difference for any year was found for COD, BOD and TSS indicating that varying HLR and SLR does not significantly impact filtrate quality and suggests that most organic matter is tied to the sludge solids and is effectively removed through filtration. No significant differences in TN and TP were observed in 2007, 2010 and 2011, with some significant differences found in 2008 and 2009, although not important from a treatment perspective. It can be concluded from these results that a combined sand bed-freezing bed or reed bed-freezing bed technology can effectively separate organic matter and nutrients from septage at SLRs between 43 and 147 kg/m^2/y and HLRs between 1.9 and 5.9 m/y, with little to no effect on filtrate quality. Furthermore, differences between the planted RB1 andRB2 compared with the unplanted SF were mostly not significant and where significance was found, the differences were also not important from an effluent quality perspective.

The effect of operating period (freezing-thaw vs reed bed) and accumulating sludge cake with time on filtrate quality is presented in Figure 3. Significant differences between Periods were observed for COD, TSS, TP and TN ($P<0.05$), while no significant differences were observed between Years ($P>0.05$). A pattern of higher concentrations in the FT period can be observed for all parameters except TN, which displays the opposite pattern. Higher solids migration observed during thawing events could result from preferential pathways created from FT conditioning of the sludge cake in conjunction with higher levels of soil saturation (Mohanty et al., 2014). The higher concentrations of nitrogen observed from May to November (G) could result from higher dissolved ammonia concentrations in the raw septage, as proportionally more holding tanks, with lower strength wastewater, are pumped during winter. While filtrate is observed to vary by operating period, no trend over time was observed, indicating that the accumulating sludge cake does not affect filtrate quality and that the filters are operating in a steady state condition.

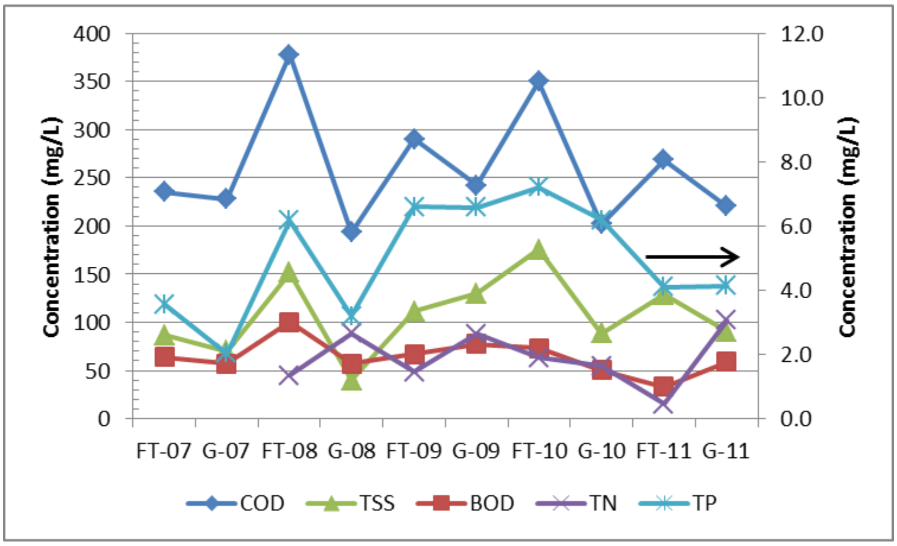

Figure 3. Filtrate quality with time comparing freeze-thaw (FT) period from December-April to the growing (G) period from May-November. Each period is an average of the three filters. Error bars not shown for clarity. A two-factor ANOVA with average concentration from the three filters as replicates was used. Significant effect of Period for COD, TSS, TN and TP was observed ($P<0.05$), while no effect for Year ($P>0.05$) was observed.

Dewatered septage cake quality is described in Table 3 and is compared with raw septage and solid dairy manure. Solids increased from 2.6 to 23.8 percent dry matter (d.m.), which is comparable to solid dairy manure. Approximately 25% of nitrogen is lost in the filters (on a d.m. basis), likely from nitrification/denitrification reactions, with dried septage cake containing 78% of solid dairy manure N. P is almost entirely conserved in the sludge cake and is somewhat higher than that of solid dairy manure. Septage, however, is not a significant source of K compared with solid dairy manure as K is water soluble and is not strongly bound to the sludge solids. No change is organic matter (OM) between raw septage and dried septage cake was observed, suggesting that the readily degradeable organics in domestic wastewater have already been largely consumed by anaerobic bacteria in the septic tanks prior to application to the filters. OM is lower in the dewatered septage compared with solid dairy manure, reflecting the more stabilized nature of septage, while total carbon concentrations were the same between the two materials at 36% (on a d.m. basis). The C/N ratio in the dried septage cake is somewhat higher than solid dairy manure, while the NH_4/TKN ratio is lower, reflecting the loss of ammonia in the filter beds. In summary, the dried septage cake can provide a good source of organic matter and nutrients for agricultural production and has similar agronomic value to solid dairy manure.

Table 3. Nutrient Content in Dewatered Septage. Average of three filters (Avg. ± SD)

Parameter	Raw Septage	Dewatered Septage Cake	Solid Dairy Manure
Dry Matter (%)	2.6 ± 2.4	23.8 ± 6.9	25.9*
OM (%)	65±13	63±3	72**
C (% d.m.)	-	36.0±1.8	35.6**
N (% d.m.)	2.91 ± 2.43	2.09 ± 0.49	2.78*
P (% d.m.)	1.03 ± 1.15	0.96 ± 0.01	0.77*
K (% d.m.)	0.36 ± 0.60	0.13 ± 0.05	2.36*
C/N	-	17.2	12.8**
NH_4^+/TKN	0.17	0.08	0.21*

* Brown, C. (2013) Available Nutrients and Value for Manure from Various Livestock Types OMAFRA FactSheet;

**Pettygrove and Heinrich (2009). Dairy Manure Content and Forms, UC Extension.

Metals

The regulated metals were evaluated in the dewatered septage cake at the end of year 4 and are presented in Table 4 and compared with both domestic sludge and the regulatory limits for Ontario, Canada. The dewatered septage cake had lower concentrations than municipal sludge for most metal species, with similar values observed for Cu, Mo, Se and Zn. This stands to reason, as municipal sludge derives from mixed domestic and industrial sources, which could increase metals content. No significant differences in the sludge metal concentration were observed between the three filters (P>0.05), with values substantially below the CM2 regulated limits; however, several species where higher than the CM1 limits. These results indicate that dewatered septage cake meets the CM2 metals limits for restricted land application in Ontario. It should also be noted that the septage cake meets the USEPA exceptional quality (EQ) metals standard for unrestricted land application (Iranpour et al., 2004); which is considerably less stringent than Ontario's CM1 Standard.

Table 4. Dewatered Septage Cake Concentrations and Limits for Regulated Metals (mg/kg d.s.)

Regulated Metal	Typical Domestic Sludge (USEPA, 1984a)	Dewatered Septage Cake (Avg. ± SD)			Land Application Metal Limits (O.Reg.267/03)	
		RB1	RB2	SF	CM1	CM2
As	10	*<2.5	*<2.5	*<2.5	13	170
Cd	10	2.8±0.2	2.2±0.3	2.6±0.3	3	34
Co	30	1.8±0.1	1.6±0.3	1.7±0.3	34	340
Cr	500	35±5	25±2	26±5	210	2,800
Cu	800	722±117	518±85	695±54	100	1,700
Pb	500	68±8	94±24	60±20	150	1,100

Hg	6	*<2.2	*<2.2	*<2.2	0.8	11
Mo	4	9.2±0.9	7.1±1.9	9.0±1.2	5	94
Ni	80	23±3	20±2	22±2	62	420
Se	5	8.3±2.6	7.5±2.7	7.5±2.7	2	34
Zn	1700	1267±103	1110±217	1113±82	500	4200

* less than method detection limit value

Pathogens

E.coli filtrate numbers were reduced from 7.2±0.9 log CFU/100mL in raw septage to annual averages ranging from 5.3±0.2 log CFU/100mL in Year 1 to 4.4±0.2 log CFU/100mL in Year 5, with log reductions of between 1.9 and 2.8. While there is no pathogen standard for irrigation water in Ontario, WHO (2006) recommends <5 log *E.coli* CFU/100mL for restricted irrigation with treated wastewater while USEPA (2012) recommends <3 log *E.coli* CFU /100mL. On average, the filtrate would meet a 5 log limit; however, would not meet a 3 log limit without further treatment.

Average annual *E.coli* numbers in the sludge cake with cumulative sludge cake depth are presented in Figure 4. No significant differences between the three filters was observed (P>0.1), while a significant difference between years was observed (P<0.01). *E.coli* numbers are shown to decline from Years 1-4, with a levelling off in Year 5 with a very strong negative correlation with sludge cake depth (R=-0.95). This suggests that as sludge cake depth increases, the impact of new sludge dosing diminishes, which is consistent with observations of Nielson (2007), who found a sharp reduction in pathogen numbers in the first 40 cm of a reed bed shortly after dosing. During years 4 and 5 the *E.coli* numbers were below the limit for restricted land application of biosolids in Ontario and other jurisdiction of 2 x 10^6 *E.coli*/g d.m. (CCME, 2010); therefore, in principal the sludge cake could be removed and land applied without requiring further treatment such as composting or lime stabilization.

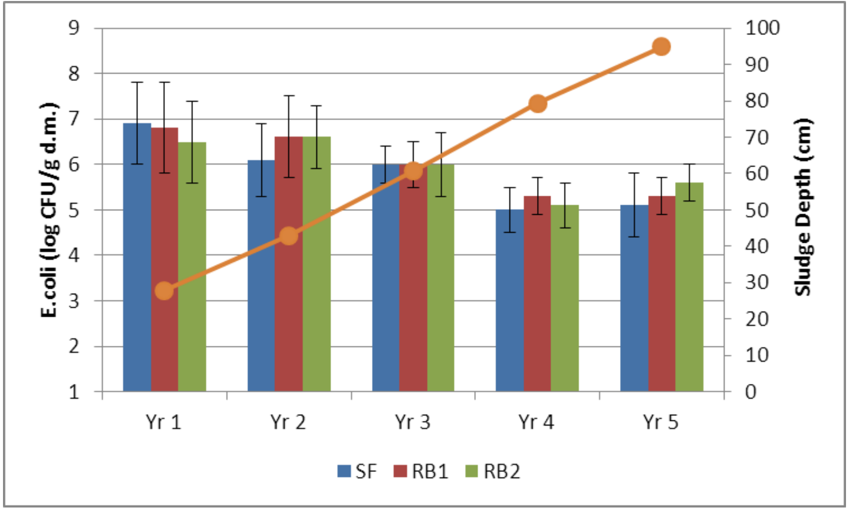

Figure 4. Dewatered sludge cake *E.coli* with time during filter operation (Yearly geometric mean ± SD) and average sludge cake depth of three filters. Two-way ANOVA with Filter and Year as variables. No significant difference between Filters (P>0.1) while significant difference between Years (P<0.01).

CONCLUSIONS

A combined reed bed-freezing bed technology was effective at treating septage under Canadian climatic conditions over a period of 5 years of continuous dosing with average loading rates of 82-104 kg TS/m^2/y. Varying hydraulic and solid loading rates as well as the increasing sludge cake with time had little to no effect on treatment efficiency, with 99% removal of BOD and TSS in addition to many heavy metal species, 98% removal of TP and 90% removal of TN; suggesting that these contaminants are largely tied to sludge solids and are effectively removed through filtration. Filtrate quality was consistent with a low to medium strength domestic wastewater which is easily treatable in any municipal or decentralised wastewater system. The potential for reuse as irrigation water will depend upon local regulations.

The dewatered sludge cake consistently met biosolids land application standards in terms of pathogen and metals content, with *E.coli* numbers declining with time as sludge cake depth increased. The sludge cake exhibited similar dry matter, organic matter, carbon, nitrogen and phosphorus content to solid dairy manure and can provide an excellent source of nutrients and organic matter for crop production.

A combined reed bed – freezing bed technology can provide a low cost solution for septage management in rural communities in cold-climate regions with potential for beneficial reuse of both the filtrate and dewatered sludge cake.

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