



RESILIENT INFRASTRUCTURE

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SOIL AQUIFER TREATMENT OF SECONDARY EFFLUENTS AND CSOS IN SOUTHWESTERN ONTARIO

Diego Velasquez (PhD Candidate)
Western University, Canada

Dr. Ernest Yanful
Western University, Canada

Weijian Sun (M.Eng.)
Western University, Canada

ABSTRACT

Wastewater reclamation is becoming an important alternative for sustainable water resources management and building climate change resiliency in many regions around the world. The purpose of this research was to investigate the polishing of secondary effluents and Combine Sewer Overflows (CSOs) by a laboratory scale Soil Aquifer Treatment (SAT) considering local sub-surface geology and wastewater characteristics. Results show that characteristic soils of southwestern Ontario can effectively polish secondary effluents in terms of BOD₅ (64.9% to 100%), e-coli (100%) and total coliforms (100%). However, low removals of DOC (22.81%) and Nitrate (15.17 %) were achieved. Furthermore, low to moderate improvements of CSOs quality were observed with maximum removals of 54.26 % for BOD₅, 36.67% for e-coli, 58.15% for total coliforms and 44.83 % for Total Nitrogen. Additionally, de-nitrification of secondary effluents was greatly improved (46.1 % to 100%) by the addition of readily available organic matter, which supports the importance of protecting recharge wetlands for groundwater quality protection. SAT in southwestern Ontario is a feasible alternative for the recharge of non-potable and potable aquifers with secondary effluents. However, for potable aquifers further treatment of wastewater effluents may be required.

Keywords: Soil Aquifer Treatment, resiliency, water resources management, wastewater reclamation, sustainability.

1. INTRODUCTION

Water resources around the world are under increasing pressure from the rapidly growing demands of rising population and industrialization. Furthermore, changes in global weather patterns are expected to intensify its current and future stresses. Searching for alternative sources of water such as the recovery of rain water, desalination of seawater or brackish groundwater, on-site grey water reuse and the reclamation of municipal waste are important approaches to reducing the pressure on fresh water availability (NRC 2012). Reclamation of highly treated wastewater has become a feasible alternative for augmenting drinking water supplies, such as groundwater and surface waters, largely as a result of advances in treatment technology that enables the production of high quality recycled water at increasingly reasonable costs and reduced energy inputs (Rodriguez et al. 2009).

Advantages of aquifer storage over surface water reservoirs includes a higher capacity of storage, lower requirements for land, lower costs, prevents evaporation and by recharging through unsaturated soil layers it can provide additional purification to the treated effluent (Dillon et al. 2006, Wintgens et al. 2008). Groundwater recharge can be achieved by the direct injection of treated wastewater into the aquifer or by allowing the treated wastewater to infiltrate and percolate through the soil into the aquifer. The latter is also known as Soil-Aquifer Treatment (SAT). SAT involves the infiltration of the wastewater effluent through a recharge basin followed by the recovery of the purified wastewater through recovery wells. The pollutants removal mechanism involves physical, chemical and biological processes in the unsaturated and saturated zones. Several field and laboratory-scale studies

have been carried out around the world to determine the effectiveness of SAT at removing specific pollutants. Therefore, it can be safely stated that the performance of SAT systems is mainly affected by the quality of influent wastewater, the specific characteristics of the site (climate, geology and hydrogeology) and the operational schedule of the infiltration basins (Harun 2007, Sharma et al. 2008). Main water quality concerns of wastewater reclamation subjected to SAT include organics, nitrogen species, pathogens and emergent contaminants such as pharmaceuticals (Dolnicar and Schafer 2009). The purpose of this research was to investigate the prospect of Soil Aquifer Treatment of secondary effluents and combined sewer overflows for indirect potable or non-potable reuse taking into consideration local wastewater characteristics and subsurface geology of southwestern Ontario.

2. STUDY SITE

Southwestern Ontario is a secondary region in southern Ontario, with a population of approximately 3.5 million. Main sources of drinking water in southwestern Ontario include the Great Lakes (Lake Erie and Lake Huron) and groundwater. The current surficial deposits and landscape of southwestern Ontario are mainly the result of the last glaciation, known as the Wisconsin glacial events, leaving behind sediments such as tills, glaciofluvial sand and gravel, glaciolacustrine and glaciomarine silts and clays (Chapman and Putnam 1984, OGS 2010). Soils permeability in southwestern Ontario varies from high to low (29 % high, 65 % low and 6% variable) throughout the region (OGS 2010). High permeability soils would be preferable over low permeability for surface infiltration systems to maintain high infiltration rates and minimize land requirements (Bouwer 2002). Additionally, when high permeability soils in southwestern Ontario are classified according to material description, fine to medium grained sands are the most prevalent (OGS 2010).

3. MATERIALS AND METHODS

A laboratory scale soil aquifer treatment was built taking into consideration the predominant surficial deposits of southwestern Ontario (fine to medium grained sands). The SAT system was built using a polyvinyl chloride (PVC) column with an internal diameter of 5 cm and effective length of 90 cm. A series of sampling ports that extended from the center of the column's cross section were installed at multiple depths from the soil surface at 0, 10, 30, 50, 70, 90 cm. The SAT system was operated under gravity flow conditions at a constant head of 20 cm, which was maintained by the use of a top feeding tank with an overflow weir, a peristaltic pump and flexible PVC tubing. Additionally, a valve was installed at the outlet to be able to control the outlet flow and, therefore, hydraulic retention times. Figure 1 shows a schematic representation of the experimental set up.

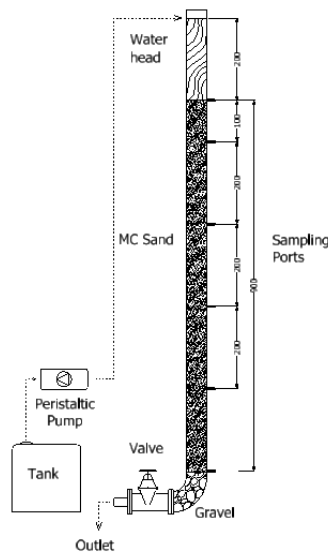


Figure 1: Schematic representation of the experimental set up

The column was packed with natural fine to medium natural sand collected from the banks of the Medway Creek (MC), a tributary of the Thames River in London, Ontario. The collected MC sand was washed, dried for 72 hours at 65 °C and sieved before packing the column. The sieving was performed to remove sand particles smaller than 0.125 mm (U.S. standard mesh 120) and higher than 0.5 mm (U.S. standard mesh 35) in order to represent high permeability aquifer recharge zones with fine to medium grain size distribution. Subsequently, the effective length of the column was packed to a typical dry bulk density of sandy soils of 1.52 g/cm³. The bottom 20 cm of the column were filled with gravel to support the sand. Graphic geometric mean and standard deviation were measured as 1.9 Φ and 0.55 Φ (moderately well sorted) respectively. Specific gravity was measured as 2.65.

The laboratory scale SAT system was operated with wastewater for a period of 10 consecutive months (March – December, 2014) on cycles of 7 days wetting and 7 days drying at 20 °C (\pm 1°C). After a wetting cycle of several days, a drying cycle is usually necessary to restore surface permeability and increase the column redox potential (Bouwer 2002). The SAT system was operated at 3 hydraulic retention times representative of high permeability soils. Simulated combined sewer overflows (CSOs) were prepared in the laboratory by diluting raw wastewater with distilled water at a ratio of 1:2 (Gandhi et al. 2014). A summary of the experiments performed during the 10 months of operation is presented in table 1.

Table 1: Summary of experiments

Experiment	Wet/Dry cycles	Column influent	Outlet Flow (ml/min)	HRT (hours)	K (m/d)
A	3	Secondary Effluent	10	1.4	5.3
B	3	Secondary Effluent	5	2.8	2.7
C	3	Secondary Effluent	1	13.9	0.5
D	2	Combined Sewer Overflows	5	2.8	2.7
E	2	Secondary + methanol (C/N 1:1)	5	2.8	2.7
F	2	Secondary + methanol (C/N 1:3)	5	2.8	2.7
G	2	Secondary + methanol (C/N 1:6)	5	2.8	2.7

Secondary effluent and raw wastewater were collected from the Adelaide Pollution Control Plant (APCP) in London, Ontario, and stored at 4 °C in 5 gallons high density polyethylene drums. Before introducing the wastewater into the system, it was allowed to acclimatize to the column operating conditions. The APCP provides secondary level treatment to domestic and industrial wastewater by the activated sludge process and discharges its treated effluent into the Thames River, a tributary of the Great Lakes. The activated sludge process at the APCP is designed to provide both BOD removal and nitrification. Phosphorous removal is achieved by chemical addition and disinfection, between April 1 and September 30, by ultraviolet light (City of London 2015). Average raw and final effluent characteristics at APCP in 2014 are shown in Table 2.

Table 2: Average secondary effluent characteristics at APCP in 2014 (units in mg/L)

	Raw	Secondary
Temp (°C)	16.8	n/a
BOD (mg/L)	128	3
Suspended Solids (mg/L)	153	3
Total Phosphorus (mg/L)	4.2	0.58
Free NH ₃ (mg/L)	18.1	0.4
TKN (mg/L)	29.1	1.8
Unionized Ammonia (mg/L)	n/a	0.003
NO ₃ ⁻ N(mg/L)	n/a	16.4
e-coli (G.M.)	n/a	8

Source: City of London, 2015

Samples were collected on the last day of the wetting cycle, filtered with a 0.45 µm membrane filter when necessary and stored at 4°C prior to analysis. Secondary effluents utilized for experiments A, B and C were analyzed for Dissolved Oxygen (DO), Dissolved Organic Carbon (DOC), *Escherichia coli* (e-coli), total coliforms, ammonia (NH₃), phosphate ions (PO₄³⁻), Nitrate ions (NO₃⁻) and Sulphate ions (SO₄²⁻) at all column depths. Simulated CSOs used for experiment D were analyzed for Dissolved oxygen (DO), Biological Oxygen Demand (BOD₅), Total Nitrogen (TN), total coliforms and e-coli at all column depths. Experiments E, F and G were analyzed for dissolved nitrate ions (NO₃⁻) at all column depths. Dissolved oxygen was also measure at the column inflow and effective length of 90 cm every 24 hours. Secondary effluent was introduced into the system for a consecutive period of 4 weeks to allow for biofilm formation before the start of the experiments.

3.1 Analytical Techniques for Water Constituents

Dissolved Nitrate (NO₃⁻), Sulphate (SO₄²⁻) and phosphate (PO₄³⁻) ions were measured using High Performance Liquid Chromatography (HPLC) with a Conductivity Detector (Waters 432). Ammonia nitrogen and total nitrogen were measured by the salicylate method (Hach method 10031) and persulfate digestion method (Hach method 10071) respectively. Total coliforms and *Escherichia coli* (*E. coli*) were measured by Membrane Filtration Method (10029). Dissolve Organic Carbon was measured using a SHIMADZU TOC analyzer for solids (SSM-5000A) and liquids (TOC-VCS/CP). Dissolve Oxygen was measured at the time of sampling using a portable digital meter (Hach HQ30d – DO) and Biological Oxygen Demand (BOD₅) was measured following the standard method for the examination of water and wastewater (Method 10230).

4. RESULTS

4.1 Dissolved Oxygen (DO) consumption

Dissolved oxygen in the wastewater was measure every day during the wetting cycle at inflow and outflow (90 cm) as an indicator of biofilm growth and stabilization. On the last day of the wetting cycle it was measured at all sampling ports. The first measurements of inflow and outflow DO were taken 24 hours into the wetting cycle, followed by consecutive measurements every 24 hours until the end of the wetting cycle. Average inflow DO was measured as 8.04 mg/L (SD= 0.42) and 5.9 mg/L (SD= 0.70) in the secondary effluents and simulated CSOs respectively. Table 3 shows average daily percentage DO consumption for experiments A, B, C and D.

Table 3: Average daily DO consumption (%) – 7 days wetting cycle

Day	EXP. A (n=3)		EXP. B (n=3)		EXP. C (n=3)		EXP. D (n=2)	
	% DO Red	SD	% DO Red	SD	% DO Red	SD	% DO Red	SD
1	13.35	1.95	26.65	0.54	50.43	0.87	11.54	4.56
2	39.03	6.13	55.09	2.69	59.93	0.71	26.85	6.55
3	45.16	12.49	61.32	0.43	67.91	0.61	38.13	7.09
4	59.34	6.18	66.69	5.19	68.67	0.33	49.24	3.87
5	61.66	1.15	68.41	0.70	73.55	0.62	48.17	0.47
6	58.11	4.40	66.63	0.88	77.27	0.94	50.00	4.68
7	62.88	0.45	73.06	1.28	77.64	0.89	49.78	0.72

Additionally, samples taken from all the ports (0, 10, 30, 50, 70, 90 cm) on the 4 day of wetting were analyzed for dissolved oxygen. The average DO consumption at the last day of the wetting cycle was 62.69 %, 72.32 % and 77.64 % for experiments A, B and C respectively. Average DO consumption at the last day of the wetting cycle for experiment D was 51.50 %.

Results show (see table 4) that oxygen consumption during the wetting cycle is proportional to the hydraulic retention time for experiments with secondary effluent. Additionally, after approximately 3 days of operation, dissolved oxygen consumption does not change significantly for the remaining of the wetting cycle. This suggests that the biofilm reaches a quasi- steady state after a few days of column operation. It is also observed in experiments A, B, C and D that the largest DO reduction occurs during the first 30 cm of the soil column. This is attributed to higher biological activity of heterotrophic bacteria in the aerobic zone of the column. These results are

also consistent with previous soil aquifer treatment studies that show the important role of the first few cm of the soil in the treatment process (Essandoh et al. 2013, Harun 2007). No clogging of the column was observed during the experiments conducted with secondary effluent (A, B and C). However, an average reduction of surface permeability by 31% was observed after 7 days of wetting for experiment D with CSOs. This is expected due to the presence of particulate and colloidal organic matter in raw wastewater.

Table 4: Percentage DO reduction by column depth

Depth (cm)	EXP. A (n=3)		EXP. B (n=3)		EXP. C (n=3)		EXP. D (n=2)	
	% DO Red	SD	% DO Red	SD	% DO Red	SD	% DO Red	SD
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	32.80	5.83	29.07	5.41	38.43	1.44	23.54	11.12
30	60.34	5.83	57.61	2.10	64.04	1.92	48.42	6.33
50	61.23	6.19	68.69	1.65	71.35	0.50	50.58	4.14
70	61.74	3.32	69.72	2.50	74.72	4.83	49.92	2.05
90	62.69	0.18	72.32	5.48	77.64	1.89	51.50	2.56

4.2 Organic matter

Dissolved organic carbon (DOC) was measured at all the sampling depths, while BOD₅ was only measured at the inflow and at the 90 cm depth, for experiments A, B and C. Organic matter in secondary effluents from biological treatment is mainly composed of natural organic matter, easily biodegradable organic carbon, soluble microbial products and synthetic organic compounds such as disinfection by-products (Fox et al. 2005). SAT has shown to remove easily biodegradable carbon and synthetic organic compounds (Drewes and Fox 1999; Fox 2002). Average DOC and BOD₅ in the secondary effluent of APPC were measured as 36.15 mg/L (SD= 2.99) and 3.30 mg/L (SD =1.00) respectively. Results show the majority of the DOC consumption occurs during the first 50 cm of the column and reaches a maximum of 7.54 %, 20.58 % and 22.81 % at the 90 cm depth for experiments A, B and C respectively. Average BOD₅ reduction at the 90 cm depth by experiments A, B and C was 64.09 %, 84.39 % and 100 % respectively.

Biodegradable organics in simulated CSOs were measured as BOD₅. Biodegradable organic matter in municipal wastewater is mainly found as carbohydrates, proteins and grease (fats). Average BOD₅ in the simulated CSO was measured as 19.35 mg/L (SD=3.18). Results show the majority of BOD₅ removal occurs during the first 30 cm of the column and reaches a maximum of 54.26 % at the 90 cm depth. DOC and BOD₅ results are shown in tables 5 and 6.

Table 5: Percentage DOC reduction by column depth

Depth (cm)	EXP. A		EXP. B		EXP. C	
	% DOC Red	SD	% DOC Red	SD	% DOC Red	SD
0	0.00	0.00	0.00	0.00	0.00	0.00
10	2.35	0.12	7.74	1.39	9.35	0.33
30	3.29	0.13	9.81	2.49	13.96	0.97
50	5.75	0.68	16.28	4.99	20.03	1.08
70	6.97	0.79	18.33	0.74	21.84	0.70
90	7.54	0.67	20.58	0.58	22.81	2.25

Table 6: Percentage BOD₅ reduction by column's effective length

Depth (cm)	EXP. D	
	% BOD Red	SD
0	0.00	0.00
10	10.85	0.49
30	45.74	4.41
50	54.00	0.95
70	55.04	2.15
90	54.26	0.87

Removal of DOC from secondary effluents showed dependency of both retention time and column depth up to approximately 50 cm. A maximum DOC removal of 22.81 % from secondary effluents was achieved at experiment C, which had the longest retention time. However, removal of DOC from secondary effluents was relatively low due to the soil type and hydraulic retention times. Previous SAT studies have also shown that DOC removal by fine to medium sands is low when compared with sandy loams and clay lenses that can achieve removals as high as 85 % (Quanrud et al. 2003, Westerhoff and Pinney 2000). However, BOD₅ removal from secondary effluents at the 90 cm depth was significantly higher reaching a maximum of 100 % at experiment C. It can be concluded that secondary effluents can be effectively polished in terms of the removal of readily available organic matter, but other forms of organic matter may require longer retention times.

Mechanisms of organic carbon removal in SAT is a combination of biodegradation and absorption. However, the sustainability of SAT systems depends on biodegradation (Fox et al. 2005). Biodegradation occurs under different electron acceptors depending of the redox conditions (aerobic, anaerobic or anoxic). Organic matter reduction shows that the SAT column operates under aerobic conditions at the three retention times, where DO is the main elector acceptor. Linear correlations are observed between % DO consumption and % organic matter reduction, with stronger linearity at higher hydraulic retention times (0.761, 0.952, 0.903 and 0.930 for experiments A, B, C and D respectively). See figure 2. The strong linearity suggest organic matter reduction is mainly due to biological activity.

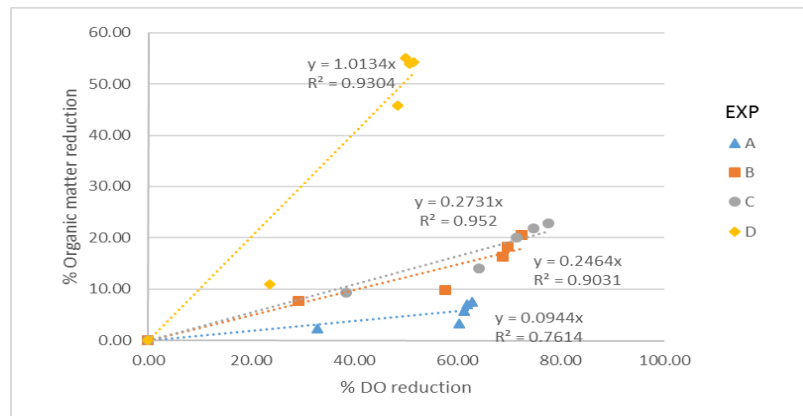


Figure 2. Average % organic matter reduction vs average % DO consumption

4.3 E-coli and total coliforms reduction:

Bacteria and viruses in secondary effluents are removed during Soil Aquifer Treatment by a variety of processes such as filtration, predation and adsorption. Removal efficiencies are affected by the retention time, grain size distribution, size of microbes, and the ability of microbes to persist in soil (Harun 2007). Geometric mean e-coli concentrations in the secondary effluent and CSOs were measured as 179 CFU/100 and ml 750 CFU/100 ml respectively. Additionally, Geometric mean total Coliform concentrations in the secondary effluent and CSOs were measured as 1416 CFU/100 ml and 6750 CFU/100 ml respectively. E-coli was 100 % removed at the 90 cm depth at

experiments A, B and C, with most of the removal occurring during the first 50 cm of the soil column. However, e-coli is only removed by 36.67 % from the simulated CSOs. Likewise, total coliforms are almost 100 % removed at the 90 cm depth at experiments A (100 %), B (99.26 %) and C (99.22%), and only 58.15 % from the simulated CSOs. Percentage reductions of e-coli total coliforms concentration are shown in Tables 7 and 8 respectively.

Table 7: Percentage E-coli reduction by column depth

Depth (cm)	EXP. A		EXP. B		EXP. C		EXP. D	
	% E-Coli		% E-Coli		% E-Coli		% E-Coli	
	Red	SD	Red	SD	Red	SD	Red	SD
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	-16.67	7.86	-34.00	5.66	53.13	66.29	-56.67	33.00
30	72.22	39.28	50.00	28.28	96.88	4.42	-3.33	4.71
50	100.00	0.00	95.00	7.07	96.88	4.42	0.00	0.00
70	100.00	0.00	100.00	0.00	96.88	4.42	36.67	4.71
90	100.00	0.00	100.00	0.00	100.00	0.00	36.67	23.57

Table 8: Percentage total coliforms reduction by column depth

Depth (cm)	EXP. A		EXP. B		EXP. C		EXP. D	
	% T.C.		% T.C.		% T.C.		% T.C.	
	Red	SD	Red	SD	Red	SD	Red	SD
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	-4.05	1.91	-74.70	138.64	69.73	9.67	54.44	5.76
30	63.51	28.67	36.36	19.28	51.95	59.66	54.44	3.67
50	81.08	26.76	54.55	6.43	75.98	32.32	71.11	6.29
70	95.95	5.73	97.61	0.16	98.83	1.10	52.96	6.81
90	100.00	0.00	98.26	0.11	99.22	0.00	58.15	5.76

Results show the removal of e-coli from secondary effluents occurs during the first 50 cm of the soil column and reaches a maximum of 100% for experiments A, B and C. Although an increase of e-coli concentration may be observed during the first 20 centimeters of the column due to the high biological activity, it is successfully removed by the effective length of the column. Total coliforms reduction is also substantial for experiments A, B and C, approaching nearly 100 % removal at the 90 cm depth. Most of the total coliforms removals for the experiments with secondary effluent occurs at 70 cm depth. The Ontario Drinking Water Standards, Objectives and Guidelines specifies non detectable concentrations of e-coli and total coliforms in drinking water sources. E-coli and total coliforms removal from CSOs (experiment D) are poor to moderate, reaching a maximum removal of 36.9 % and 58.15% respectively at the 90 cm depth.

4.4 Nitrogen removal

Nitrogen removal was measured as Nitrate (NO_3^-) and Total Nitrogen (TN) for the experiments with secondary effluents and CSOs respectively. The main form of nitrogen found in the secondary effluents from APCP is nitrate (APCP, 2015). Nitrogen in simulated CSOs is mainly present as ammonia and organic nitrogen. Nitrate removal is achieved by the reduction of nitrate to nitrogen gas through nitrite, nitric and nitrous oxide intermediaries by heterotrophic bacteria. Generally, denitrification occurs when most oxygen has been consumed and nitrate becomes the next electron donor. However, studies have shown that at a completely anaerobic environment is not required for denitrification to occur in soils (Essandoh et al. 2011). Average nitrate concentration in the secondary effluent was measured as 18.37 mg/L NO_3^- - N (SD=4.04 mg/L). Results show that nitrate removal from secondary effluents by SAT was not achieved at retention times of 1.4 and 2.8 hours (experiments A and B). However, at HRT of 13.1 hours (experiment C), an average 15.17 % reduction was achieved at the 90 cm depth. Average total nitrogen in the simulated CSOs was measured as 23.2 mg/L (S.D.=1.20 mg/L) with a 42.9 % removal at the 90 cm depth. Results are shown in Table 9.

Table 9: Percentage Nitrogen reduction by column depth

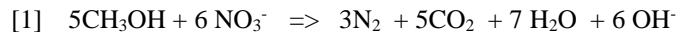
Depth (cm)	EXP. A	EXP. B	EXP. C		EXP. D	
	% Nitrate Red	% Nitrate Red	% Nitrate Red	SD	% Total N Red	SD
0	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	3.46	0.56	9.94	4.84
30	0.00	0.00	12.35	0.13	13.52	4.65
50	0.00	0.00	13.98	0.36	21.58	3.69
70	0.00	0.00	14.81	1.30	37.45	11.51
90	0.00	0.00	15.17	1.46	42.90	6.42

Average TKN, Nitrate, free ammonia and un-ionized ammonia in secondary effluents measured as nitrogen are 2 mg/L, 16.4 mg/L, 0.4 mg/L and 0.003 mg/L respectively. There are not guideline values for ammonia concentrations in the Ontario Drinking Water Standards, Objectives and Guidelines (2003) due to the fact that it is naturally produced in the body and efficiently metabolized in healthy people (Health Canada 2014). Organic nitrogen and nitrate limits by the Ontario Drinking Water Standards, Objectives and Guidelines are 0.15 mg/L and 10 mg/L (measured as Nitrogen) respectively. However, organic nitrogen recommendations are mainly an operational guideline. Nitrate in drinking water poses more serious health issues, such as Methaemoglobinaemia (blue baby syndrome) and effects on thyroid gland function in bottle-fed infants (Health Canada 2014). Therefore, nitrogen species are one of the most common reasons that groundwaters do not meet drinking water standards (AWWA-RF 1998). Average Nitrate concentrations in secondary effluents are above the limit of 10 mg/L set by the Ontario Drinking Water Standards, Objectives and Guidelines. Even after the 15.17% removal achieved in experiment C, the nitrate concentration is higher than the accepted limit. Redox conditions and the limited availability of readily available organic matter for heterotrophic denitrification are the main reasons for the low nitrate removal by the SAT system. However, several studies have shown that denitrification in soil can occur under aerobic conditions even at concentrations close to air oxygen saturation (Essandoh et al. 2013). Average Total Nitrogen removal from simulated CSOs was 43.8 % at the 90 cm depth due to nitrification and absorption. Ammonia is consumed by a combination volatilization and adsorption with subsequent nitrification, which would yield high concentrations of nitrate in the effluent (Essandoh et al. 2013).

Concentrations of orthophosphate and ammonia in the secondary effluent from the APCP were below detectable levels at all column depths for all retention times. Additionally, dissolved sulphate ions, measured as 41.87 mg/L (SD=3.23) and 27.47 mg/l (SD= 1.24) in secondary effluents and simulated CSOs respectively, were not removed at any of the column depths for experiments A, B, C and D.

4.5. Enhance nitrate removal from secondary effluents

Since Nitrate ions were not significantly removed at experiments A and B, and only slightly removed (15.17 %) at experiment C, enhance Nitrate removal from secondary effluents with the addition of readily available organic matter was investigated. Methanol was used as organic matter source, which is the most commonly employed external carbon source due to being easily assimilated by denitrifying bacteria and its low cost. The optimal methanol: NO₃⁻ ratio for biological denitrification in packed column or suspended growth reactors is between 2:1 and 3:1 at 20 °C (EPA 1970). Reaction stoichiometric when methanol is the carbon source is shown in equation 1.



Three methanol: NO₃⁻ ratios were investigated, 1:1, 3:1 and 6:1, at experiments E, F and G respectively. All Nitrate removal experiments were conducted at a hydraulic retention time of 2.8 hours and cycles of 7 days wetting and 7 days drying. A nitrate reduction of 46.1 % (1:1), 62.7 % (3:1) and 100 % (6:1) was achieved at the 90 cm depth. Results are shown in Table 10. Methanol addition has shown that denitrification of secondary effluents was possible under aerobic conditions when readily available organic matter is provided.

Table 10. Percentage Nitrogen reduction from secondary effluents by column depth

Depth (cm)	EXP. E		EXP. F		EXP. G	
	% Nitrate Red	SD	% Nitrate Red	SD	% Nitrate Red	SD
0	0.00	0.00	0.00	0.00	0.00	0.00
10	19.77	1.13	45.88	0.09	62.98	0.13
30	26.01	2.92	60.83	1.53	69.17	0.12
50	38.21	4.47	68.58	1.39	75.36	0.12
70	37.25	2.21	66.63	1.24	84.49	0.42
90	46.12	6.55	62.69	3.89	100.00	0.00

5. CONCLUSIONS

High permeability soils of southwestern Ontario, which are mainly composed of fine to medium grained sands, have the ability to polish secondary effluents in terms of readily available organic matter (BOD₅), e-coli and total coliforms. However, issues with the persistence of nitrates affects its suitability for potable aquifer recharge. Nevertheless, when additional readily available organic matter is provided, denitrification is greatly improved. In regards to the simulated CSOs, sustainable SAT for non-potable or potable aquifer recharge is not achievable due to low removal of biological contamination, potential for high nitrate concentrations in the effluent and the occurrence of column clogging.

It can be concluded, that reclamation of secondary effluents can be an important alternative for sustainable water resources management and building climate change resiliency in south western Ontario. High permeability soils of southwestern Ontario are capable of further purifying secondary effluents for non – potable aquifer recharge. Additionally, recharge of potable aquifers may also be a possibility if secondary effluents are de-nitrified and disinfected. These findings also provide scientific support for the importance of protecting recharge wetlands in southwestern Ontario for groundwater quality protection since they can provide additional organic matter needed for denitrification.

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