8-24-2016 12:00 AM

Soil Aquifer Treatment for wastewater reclamation in a high water demand society

Diego J. Velasquez
The University of Western Ontario

Supervisor
Dr. Ernest Yanful
The University of Western Ontario

Graduate Program in Civil and Environmental Engineering
A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

Recommended Citation

Velasquez, Diego J., "Soil Aquifer Treatment for wastewater reclamation in a high water demand society" (2016). *Electronic Thesis and Dissertation Repository*. 4080.
https://ir.lib.uwo.ca/etd/4080

Abstract

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. In the present study, knowledge and perceptions towards wastewater reclamation for potable and non-potable uses were investigated by the used of an on-line survey distributed amongst the university community at Western university. Subsequent statistical analysis of the results was performed using IBM-SPSS software. Survey results show that member of the university community are more likely to accept reclaimed wastewater for applications that do not involve drinking or close personal contact. However, acceptability improves when benefits to the environment are extensive, it is safe for humans, the source of reclaimed water is perceived as cleaner than municipal wastewater, and the reclaimed wastewater is put back into natural systems with long retention times such as aquifers. Knowledge of the urban water cycle and water resources in Canada is moderate among the university community and the Gamma measure of association shows that there is a moderate (0.303) positive relationship between "water knowledge" and "close contact acceptability". The majority of the university community (75.8 %) thinks that reclaiming water to provide an alternate source of water in southwestern Ontario is a good idea, but there are still concerns with the presence of chemicals such as pharmaceuticals from reclaimed water and the long-term effects on human health from exposure to these contaminants.

Additionally, the suitability of the predominant soils of southwestern Ontario for Soil Aquifer Treatment (SAT) of secondary effluents and combine sewers overflows (CSOs) was investigated by the use of a laboratory scale SAT system operated at three hydraulic retention times. Samples were analyzed for dissolved nitrate, sulphate and phosphate ions, ammonia nitrogen, total nitrogen, total coliforms, *E. coli*, dissolved organic carbon (DOC), dissolved oxygen and biological oxygen demand (BOD_5). Results show that prevalent soils of southwestern Ontario have the ability to further polish secondary effluents in terms of organic matter, *E.coli* and total coliforms. However, issues with the persistence of nitrates affects its suitability for potable aquifer recharge. Quality of CSOs was slightly improved, however 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 media clogging.

Keywords

Wastewater reclamation, public perceptions on water reuse, sustainability, water resources management, soil aquifer treatment, climate change adaptation.

Acknowledgments

First and foremost, I am thankful to God, whose grace and blessing have given me the strength to complete this journey. I would like to express my sincere gratitude to my supervisor Dr. Ernest Yanful for his support, academic guidance and wisdom. I am thankful to Fate Hashimi for her selfless help and caring attitude. I would also like to thank Weijian Sun and Reddy Kandlakuti for the assistance they provided me.

I am especially grateful to my wife, Sally, for her continuous support, encouragement, and patience throughout this process.

Lastly, I want to express my gratitude to the Training Program in Clean Technologies for Water Refining and Nutrient and Energy Recovery (TWNER) at the University of Western Ontario for supporting this type of research that helps create a better world.

Table of Contents

List of Tables

List of Abbreviations

Activated sludge: AS

Activated sludge with biological nutrient removal: AS - BNR

Adelaide Pollution Control Plant: APCP

Biological Oxygen Demand: BOD_5

Combined Sewer Overflows: CSOs

Dissolved Air Flotation :DAF

Dissolved Organic Carbon: DOC

Dissolved Organic Nitrogen : DON

Electrodialysis : ED

Endocrine-disrupting compounds: EDC

Escherichia coli: E.coli

Ethylenediaminetetraacetic acid: EDTA

1,2-Ethanedithiol: EDT

High Performance Liquid Chromatography :HPLC

Hydraulic retention time: HRT

Membrane bioreactors: MBR

Microfiltration : MF

Nanofiltration : NF

Nitrilotriacetic acid: NTA

Pharmaceuticals and Personal Care Products: PPCP:

Reverse osmosis : RO

Soil Aquifer Treatment: SAT

Statistical Package for the Social Sciences: SPSS

Total dissolved solids: TDS

Total suspended solids: TSS

Ultrafiltration : UF

List of Figures

Chapter 1

1. Introduction to water reuse and soil aquifer treatment

Water is most commonly defined as a chemical compound consisting of two hydrogen atoms and one oxygen atom. Although this is true regarding its composition it speaks little of its importance. Above all water is life. It is essential for all living things and according to the U.S. Geological Survey (USGS) a person cannot live without water for more than one week. Nevertheless our relation to water in traditionally "water abundant" countries, such as Canada, does not reflect this reality.

The Brundtland commission's report entitled "Our Common Future" presented the concept of sustainable development, and defined it as "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" (WCED, 1987). This concept integrates economic and social development with environmental protection to ensure that natural ecosystems are not irreversibly degraded and natural resources depleted by human activities (see figure 1-1). Therefore, sustainable water resources management must aim to meet water needs reliable and equitably for current and future generations.

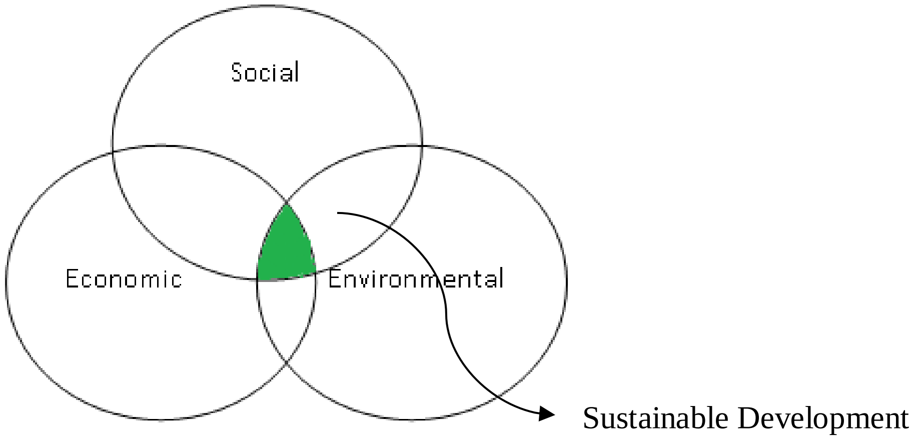


Figure 1-1: Sustainable development

Achieving sustainable water resources management around the globe is a complex task, with unique challenges to every specific region. These challenges include physical water scarcity, economical water scarcity, water quality degradation and socio-political circumstances among others. Fresh water only constitutes 3 percent of the total amount of water in the planet. And out of this 3 percent, 99 percent is locked up in icebergs, glaciers and underground (Brooymans, 2011). Global water resources are already under increasing pressure from rapidly growing demands for agriculture, production of energy, industrial uses and human consumption. Additionally, global climate change is expected to exacerbate current and future stresses on water resources from population growth and land use, and increase the frequency and severity of droughts and floods (UN, 2012).

Reducing water consumption through water conservation strategies and technological advances and searching for new water sources are the main forms of reducing the pressure on the water supply when facing physical scarcity. New water sources may include the recovery of rain and stormwater runoff, desalination of seawater or brackish groundwater, on-site grey water reuse and the reclamation of municipal wastewater effluents (NRC, 2012). Wastewater reclamation refers to the process of treating wastewater to high quality standards to render it suitable for reuse. Depending on the level of treatment, reclaimed wastewater may be utilized for potable or non-potable applications.

An alternative use for wastewater reclamation is the recharge of groundwater aquifers by allowing the treated wastewater to infiltrate and percolate through the soil into the aquifer. This presents several advantages over surface water augmentation such as 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. This process is known as Soil-Aquifer Treatment (SAT). SAT is a low cost alternative for wastewater reclamation which does not require much energy and chemical usage, making it suitable for developed and developing countries.

SAT systems for aquifer recharge are not uncommon in regions that experience water shortages and/or droughts. However, societies with high water availability lack regulatory support, public awareness and scientific research regarding wastewater reclamation. This may be driven by the general belief that Canada is a water rich country and its inhabitants do not need to worry about water shortages. The reality is that water resources are under increasing pressure from the rapidly growing demands of rising population and industrialization everywhere in world and changes in global weather patterns are expected to intensify its current and future stresses. Therefore, investigating the feasibility of SAT for wastewater reclamation in southwestern Ontario is the right step towards sustainable water resources management and building climate change resiliency.

No research has been done is southwestern Ontario regarding perceptions and acceptability of wastewater reclamation for potable and non-potable applications. Therefore, the first objective of this research was to investigate the perceptions of wastewater reuse using the university community as a representative subset of southwestern Ontario. This is an important research since public acceptance and trust of consumers in the quality of reclaimed water is considered by many to be the most important factor determining the outcomes of water reclamation projects.

The second objective of this research was to investigate the suitability and sustainability of a laboratory scale SAT system with secondary effluents and simulated CSOs. Although, several field and laboratory-scale studies carried out around the world to determine the performance of SAT systems, no research has been performed taking into consideration the predominant soils types and local wastewater effluents of southwestern Ontario. This research is an important step towards implementing actual SAT systems since previous research has shown that the performance of this systems is mainly determined 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).

Results of the first and second objectives are presented in chapter 3 and 4 respectively as integrated articles. Soil Aquifer Treatment for groundwater recharge in southwestern Ontario is a feasible alternative for sustainable water resources management and climate change adaptation as long as appropriate levels of treatment are provided for the specific intended use.

2. References

Brooymans H.(2011) Water in Canada: a resource in crisis. Vancouver, BC. Lone Pine.

Harun, C.M. (2007) Analysis of multiple contaminants during soil aquifer treatment. UNESCO-IHE MSc thesis No MWI-2007-18.

National Research Council (NRC) of the national academics. Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater. National Academy of Sciences. 2012. ISBN: 978-0-309-25749-7.

United Nations Educational, Scientific and Cultural Organization (UNESCO). The United Nations World Water Development Report. Managing Water under Uncertainty and Risk. 2012. Paris, France.

U.S. Geological Survey (USGS). North Dakota Water Science Center. Water Facts. 2014. http://nd.water.usgs.gov/ (accessed in August, 2016)

WCED (1987) Report of the World Commission on Environment and Development: Our Common Future. UN Documents. http://www.un-documents.net/wced-ocf.htm

Chapter 2

2 Literature Review

Water, one of the most essential resource needed for the survival of the human beings and life on earth in general is becoming increasingly scarce and its quality is deteriorating due to human activity. Industrialization, urbanization, and rapid population growth are the major factors affecting water quality and availability in recent times (Abel et al., 2012). A 2013 report by the World Health Organization (WHO, 2013), indicated that about 789 million people all around the world did experience an improvement in their water supply situation while other 2.5 billion people did not gain access to better-quality sanitation conditions. With the current trends in urbanization and the expansion of industrial activities, it is expected that a negative impact of human activities on the environment especially on surface waters is an unavoidable (Schmidt et al., 2007). Ground water replenishment is however a very slow process. In view of this fact, some, regions where water resources are scarce and or declining have resorted to alternatives such as wastewater reuse. In the US, water reclamation and reuse is found mostly in arid or semiarid regions such as Texas, Utah, California, Arizona, Colorado and Nevada. Highly treated wastewater has for some time now and continues to receive great interest as a valuable source of water resource (Tchobanoglous et al., 2003). The major and most important areas where reclaimed water can be applied include agricultural and landscape irrigation, industrial water reuse and ground water recharge. Due to limiting factors such as reclamation cost, safety concerns and health issues, water reuse has been more often than not limited to non potable uses. However, in areas where there is no other way of expanding fresh water supplies, the investigation and evaluation of reclaimed water for direct and indirect potable use may be an important alternative. The intended use of the reclaimed water determines to a very large extent the wastewater treatment needed in order to protect public health.

2.1 Applications of wastewater reclamation

Applications of reclaimed urban wastewater can be classified into non-potable reclamation, indirect potable reclamation and direct potable reclamation. Non-potable uses include irrigation, nature restoration, household toilet flushing and industrial process water. Indirect potable reclamation can be defined as the augmentation of natural water bodies utilized as drinking water supplies by the addition of treated wastewater. Some authors (Wintgens et al., 2008; Rygaard et al., 2011) distinguish between unintended indirect potable reuse (de facto) which occurs along major river catchments around the world, where the drinking water supplies are influenced by wastewater discharges by upstream users, and intended indirect potable reuse. Examples of intended indirect potable reclamation are aquifer and surface waters reservoir recharge. Direct potable reclamation is the introduction of reclaimed water directly into the potable water supply distribution system. Table 2.1. shows some typical treatments and uses of non- potable, indirect potable and direct potable reuse. This thesis will expand on the reclamation of wastewater effluents for indirect potable use through aquifer recharge, also known as SAT.

Type	**Typical Treatment**	**Typical Uses**
Non Potable	Biological oxidation Tertiary Filtration Disinfection Soil Aquifer Treatment	Industry – cooling towers, Toilet flushing, vehicle washing, fire protection, Unrestricted recreation Landscape, vineyards/crop irrigation
Indirect Potable	Biological oxidation Tertiary filtration Membrane filtration (MF) Reverse Osmosis (RO) Ultraviolet disinfection	Aquifer recharge Seawater barrier Surface water and Reservoir augmentation

Direct Potable	Biological oxidation Tertiary filtration MF/RO Ozone Biological active carbon Granular activated carbon UV-disinfection	Reservoir augmentation Drinking water Any other potable water use

Table 2.1: Typical treatments and uses of non- potable, indirect potable and direct potable reuse

Source: Chalmers et al., 2011

2.2 Drivers of wastewater reclamation and status around the world

Wastewater reclamation is becoming an increasingly important alternative for sustainable water resources management in many regions around the world. The highest levels of wastewater reclamation take place in regions suffering from water scarcity, such as in the Middle East, Australia, the Mediterranean and southwestern U.S.A. (Exall et al., 2006). Agriculture is by far the most important reuse option in terms of volume, basically because it accounts for 70% of total water withdrawals for all sectors/human uses (UNESCO, 2012).

The main factors driving water reclamation projects around the world have been identified as the lack of water availability, high levels of local water demand, the need for reliable sources of water, the protection of aquatic environments and stringent restrictions on effluent disposal (Jimenez and Asano, 2008; Exall et al., 2006).

Wastewater reclamation for water-intense activities such as agriculture is common in many regions of the world. In terms of volume, China, Mexico and the U.S. are the countries with the largest quantities of wastewater reuse; however, in the first two cases non-treated wastewater is included. In terms of per-capita wastewater reuse, Qatar, Israel and Kuwait attain the highest ranking, whereas in terms of wastewater reuse as a fraction of total fresh water used, Kuwait, Israel and Singapore place at the top (Jimenez and Asano, 2008).

Although reclaimed wastewater is most commonly used for agriculture and landscape irrigation (Exall et al., 2006), there are few examples of the successful introduction of reclaimed wastewater into the potable water distribution network. Singapore's NEWater and Namibia's Windhoek Goreangab Reclamation Plant are the most important wastewater reclamation projects for human consumption with a production capacity of 75,700 m^3/d and 21,000 m^3/d respectively (PUB, 2011; WABAG, 2013). In Canada, municipal wastewater reclamation has been generally conducted on a small scale or experimental basis, mainly for golf courses, urban landscape and agricultural irrigation. Industrial wastewater recycling is a more common practice, where approximately 40 % of the total water usage is recycled (Exall et al., 2006).

2.3 Challenges of wastewater reclamation

Although some of the challenges faced by wastewater reclamation projects are specific to the location where these types of developments are undertaken, there are some important prevalent obstacles to the widespread implementation of wastewater reclamation developments in many places around the world. These obstacles are summarized below.

2.3.1 Public acceptance

Public acceptance and trust of consumers in the quality of reclaimed water is considered by many the most important factor determining the outcomes of water reclamation projects (Hartly, 2006; Cain, 2011; Dolnicar and Schafer, 2009; Haddad et al.,2009; 2007; Toze, 2006). Singapore's NEWater and the Western Corridor Recycling Scheme in Brisbane, Australia are two examples of the issue (Lazarova et al., 2012). Reclaimed wastewater in Singapore branded under NEWater has been exceptionally successful in terms of public acceptance. NEWater now meets 30% of Singapore's total water demand and it is projected to meet 50% of Singapore's future water demand by 2060 (PUB, 2012). On the other hand, Brisbane wastewater reclamation still suffers from lack of public acceptance and the investment of AU$ 2.5 Billion has not be fully utilized (Lazarova et al., 2012).

A major psychological barrier to using reclaimed wastewater is its association with raw sewage, which creates discomfort in the majority of people. For this reason, wastewater reclamation advocates prefer to use the term “re-purified water” instead (Po et al., 2003). A study by the Water Reuse Foundation in which 2695 people were surveyed throughout five U.S. cities, some of which are experiencing fresh water shortages, showed that reclaimed wastewater is less likely to be rejected if it has been certified as safe by scientists, has been highly processed and has been in contact with natural systems such as aquifers and rivers for some time (Haddad et al., 2009).

Several studies (Robinson et al., 2005; Haddad et al., 2009; Po et al., 2003; Rock et al., 2008; Dolnicar and Schafer, 2009) have shown a higher degree of public acceptance for reclaimed water applications not involving close personal contact (such as industrial uses, lawn irrigation, firefighting, car washing and agricultural uses). The use of reclaimed water for applications involving drinking or close personal contact, where there is risk of human ingestion, is less acceptable. Harlty (2006) summarized the factors contributing to a higher degree of public acceptance of reclaimed water as:

- The benefits to the environment are clear
- Treatment and distribution costs are reasonable
- Trust in the technology and management of local public utilities is high
- Perception of wastewater as the source of reclaimed water and degree of human contact are minimal
- Awareness of water shortages issues is high
- Perception of the quality of reclaimed water is high

Interestingly enough, unintentional wastewater reuse, also known as de-facto wastewater reuse, is very common in many regions of the U.S. where many communities share the same river as a source for drinking water and as a sink for wastewater effluent discharge. A large fraction of a community’s drinking water originates from the wastewater effluent of upstream communities (NRC, 2012).

2.3.2 Scientific uncertainty

Treated municipal wastewater effluents are most commonly considered for water reclamation than stormwater runoff and domestic greywater. This is due to the fact that wastewater effluents are available all year around at stable flows (Toze, 2006). However, due to contamination from human waste and pharmaceuticals and personal care products (PPCP), municipal wastewater usually requires significant treatment before it can be regarded as appropriate for human use. While current water treatment technologies are able to provide suitable reclaimed wastewater for different purposes, concerns still exists in regards to water quality issues, particularly with pathogens and emerging contaminants (Dolnicar and Schafer, 2009).

A study undertaken by the U.S. Geological Survey (Kinney et al, 2006) on the presence and distribution of pharmaceuticals in soil irrigated with reclaimed wastewater suggests that the accumulation of pharmaceuticals, such as carbamazepine, in the soil organic matter may be of concern. However, it is unknown whether the persistence of pharmaceuticals in the soil at the concentrations observed by this study may present a risk to the environment or human health.

López-Serna (2011) investigated the effects of river flow augmentation through wastewater reclamation on the presence of emerging contaminants in the Llobregat River in Spain. Fifty eight pharmaceuticals were detected at low nanograms per liter concentrations, nevertheless when comparing concentrations upstream and downstream of the discharge site , the increases were not significant. It is important to keep in mind that the effects of low term exposure to low concentrations of PPCPs, its degradation by-products and metabolites, and mixtures of different PPCPs are unknown.

2.3.3 Water - Energy Nexus

Energy consumption by water treatment and transportation systems has become increasingly relevant because of the need of reliable energy sources and its links to climate change. Water and energy are also exceptionally interdependent. While most water treatment and transportation processes are energy dependent, water is extensively used for electricity production. Torcellini et al (2003) estimated the fresh water consumption for thermoelectric (fossil fuels, nuclear, or geothermal) and hydroelectric power plants in the US as 1.8 L/kWh and 68 L/kWh respectively. Energy consumption during the operational phase of water treatment systems has a large contribution to costs and environmental impacts. Furthermore, alternatives involving advanced treatment processes are more energy intensive when compared to conventional treatment (Rygaard et al., 2011). Although water reclamation projects can be energy intensive, they favorably reduce the energy consumption for the transportation of fresh water over long distances. For example, in London, Ontario, potable water is pumped from Lake Erie and Lake Huron for a combined distance of over 100 km, however, all wastewater treatment plants are located within the city boundaries.

Decisions regarding strategies for water resources management must consider the complex interconnections between water, energy and food security, and assess various aspects of sustainability to reduce risks and uncertainties. However, a comprehensive framework to compare competing interest does not currently exist in water management and planning (Asano et al., 2007)

2.3.4 Regulatory and legal support

In the U.S. there are no federal regulations governing water reclamation, consequently regulations are created and enforced at the state level. This has resulted in inconsistent regulation among states. The U.S. Environmental Protection Agency (EPA) developed the *Guidelines for Water Reuse* (U.S. EPA, 1982; 1992; 2004; 2012) to provide guidance on the state regulations and planning support. Recent estimates show that roughly 7 to 8 percent of wastewater is reclaimed in the U.S., of which 90 % take place in four states: California, Florida, Texas and Arizona (U.S. EPA, 2012). Agricultural applications are the more common uses for reclaimed wastewater in the U.S., with different regulations for fodder crops and food crops irrigation. Figure 2-1 shows a summary of reclaimed wastewater use nationwide. Wastewater reclamation regulations for crop irrigation on California, Florida, Texas and Arizona are shown in Appendix 1.

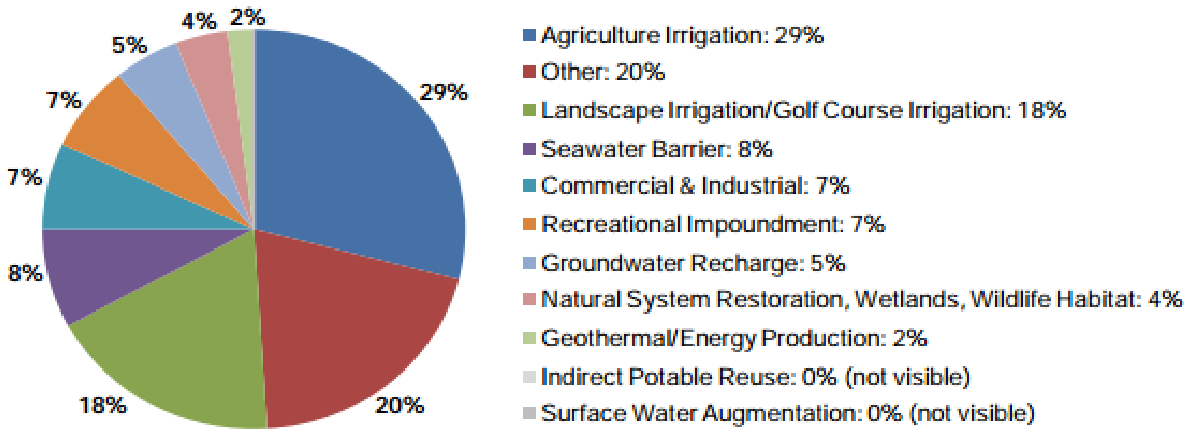


Figure 2-1. Reclaimed wastewater use nationwide

Source: U.S. EPA, 2012

California and Florida have very specific regulations for indirect potable reuse. However, direct potable reuse regulations have not yet developed in any state (Cain, 2011). Other important guidelines developed by the EPA include maximum concentrations of trace elements and nutrients for irrigation to maintain good soil characteristics and avoid desertification.

US EPA guidelines for groundwater recharge by SAT for potable and non-potable aquifers are discussed below. For non-potable aquifers, the EPA recommends a minimum of primary treatment, however, secondary treatment may be needed to prevent clogging. For indirect potable reuse, the EPA recommends secondary treatment followed by disinfection. Additionally, reclaimed water should meet drinking water standards after percolation through the vadose zone and require a setback distance of minimum 150 m to extraction wells, a vadose zone of at least 2 m deep and underground retention of at least 6 months prior to withdrawal (US-EPA, 2004).

Wastewater reclamation in Canada is very limited and there are no federal regulations wastewater reclamation and reuse. This may be driven by the general belief that Canada is a water rich country and we do not need to worry about water shortages. However, it is important to differentiate “fossil” water from renewable water. While Canada has about 20% of the world fresh water lakes, our renewable water supply only accounts for 6.5% of the world (Sprague, 2007). Also, 25 % of municipalities in Canada experienced water shortages in the last decade (Sprague, 2007). Some form of guidelines for municipal wastewater reclamation have been developed at the federal level and by the provinces of British Columbia, Alberta, Saskatchewan, Manitoba and Prince Edward Island (CMHC, 2005). British Columbia has the most comprehensive guidelines, but they are limited to urban and agricultural irrigation (CMHC, 2005). Appendix 2 shows the effluent quality regulations from the British Columbia Waste Management Act. Appendix 3 shows the reclaimed water quality criteria for Alberta, Manitoba, Saskatchewan, Manitoba and Prince Edward Island.

Regulations serve the purpose of protecting the health of the environment and people while taken advantage of the benefits of wastewater reclamation. Two major barriers to the adoption of water reclamation as strategy for sustainable water resources management are the lack of national guidelines and the lack of standards for plumbing requirements (GC, 2011). The Canadian Guidelines for Domestic Reclaimed Water for Use in Toilet and Urinal Flushing are based on risk assessments, including the identification of hazards, assessment of exposure and characterization of risks (GC, 2011).

Microbiological hazards posed the greatest risk to human health from the use of reclaimed wastewater. The Canadian Guidelines for Domestic Reclaimed Water for Use in Toilet and Urinal Flushing suggests non detected *E.coli* and Thermotolerant coliforms in the finished reclaimed water. Although bacteria (e.g. total coliforms, *E.coli*) has been traditionally used as an indicator of microbiological contamination, it does not correlate with the presence of protozoan or viral pathogens. However, protozoa and virus are of greater concern because they are harder to remove or inactivate by standard drinking water and wastewater treatment processes and, if ingested, it takes lower concentrations of them to lead to illness (GC, 2011).

2.4 Treatment technologies for environment and human health protection

The level of treatment required to make the wastewater suitable for reuse depends on the target application and the local regulations and guidelines for the protecting human health and the environment while being cost efficient. The selection of a particular technology to be added to the treatment train depends on the required effluent characteristics for a specific application and the availability of funding for capital investments and operation and maintenance.

Secondary treatment (without nutrient removal) plus disinfection can achieve effluent quality requirements for low risk non-potable applications such as surface irrigation of orchards and vineyards, non-food crop irrigation, wetland restoration, stream augmentation, and industrial cooling processes. Secondary treatment technologies include non-membrane processes (suspended growth, attached growth and hybrid systems), non-membrane processes for nutrients removal and membrane bioreactor processes (Asano et al., 2007). Appendix 4 shows the typical range of effluent quality after secondary treatment by activated sludge (AS), activated sludge with biological nutrient removal (BNR) and membrane bioreactor.

It is important to note that the removal of dissolved solids and trace metals cannot be achieved by secondary treatment; therefore, irrigation for extended periods of time may cause desertification by increasing the salinity of the soil. Disinfection is also required to achieve the pathogen concentration limits. Membrane bioreactors (MBR) are capable of achieving higher quality effluent than conventional activated sludge, however these use expensive proprietary equipment and pre-treatment are still required to avoid damaging and clogging the membrane.

Secondary treatment with biological nutrient removal followed by filtration and disinfection can achieve effluent quality requirements for non-potable applications with higher exposure to humans, such as landscape and golf course irrigation, toilet flushing, vehicle washing, food crop irrigation and industrial systems. The removal of residual particulate matter (colloidal and suspended) can be accomplished by depth filtration, surface filtration, membrane filtration (MF and UF) or dissolved air flotation (DAF).

Particulate filtration does not provide removal of dissolved solids and trace constituents. Disinfection is still required to reduce the pathogens to acceptable levels for reuse. For reclaimed wastewater applications that require higher effluent quality, such as Indirect Potable reuse and some industrial applications require the removal of dissolved solids. Indirect potable reuse applications include as the augmentation of drinking water reservoirs and aquifer recharge by direct injection. This can be achieved by pressure driven membrane separation processes such as nanofiltration (NF) and reverse osmosis (RO), and electrical driven membrane separation processes such as electrodialysis (ED). Membrane separation processes are expensive to operate because of high energy consumption and maintenance costs. Membrane fouling remains a big issue of these technologies.

Issues with dissolved solids removal by membrane processes include membrane fouling, high energy and maintenance costs, need for pre-treatment and alkalinity adjustment. The removal of specific trace organic and inorganic constituents may be necessary for reuse applications that require very high water quality such as direct potable reuse and industrial applications (semi-conductors). This can be achieved by adding unit processes to the treatment trains previously discussed. However, since the nature of the trace constituents differ from on to another, more than one technology may have to be used. The principal processes used in wastewater reclamation for the removal of trace constituent include adsorption (activated carbon), ion exchange, distillation, chemical oxidation and advance oxidation processes (Chalmers et al., 2011). An alternative to using advanced treatment technologies to achieve high quality effluents is the use of natural processes such as wetlands and SAT.

2.5 Soil Aquifer Treatment (SAT) for Indirect Potable Reclamation

Indirect potable 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 enable the production of high quality recycled water at increasingly reasonable costs and reduced energy inputs (Rodriguez et al., 2009). Indirect potable reclamation can be used to mitigate the depletion of groundwater levels, to protect coastal aquifers from saltwater intrusion, and to store surface water for future use (Wintgens et al., 2008). Furthermore, public confidence in water reclamation projects seem to be higher when the reclaimed water is put back into natural systems prior to reuse (Haddad et al., 2009; Dillon et al., 2006).

Advantages of aquifer storage over surface water reservoirs include a higher capacity of storage, lower requirements for land, lower costs, elimination of evaporation and additional purification (Dillon et al., 2006; Wintgens et al., 2008; Bdur et al., 2009). 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 SAT.

SAT is a wastewater treatment and reclamation method which makes use of soil strata to recharge soil aquifer. It has the advantage of relieving any adverse effects that can be caused when treated effluent wastewater is discharged directly into receiving surface water (Sharma et al., 2008). It is a geo-purification system in which the aquifer is recharged with partially treated wastewater through unsaturated soil strata before it mixes with the native groundwater (Bdour et al., 2009). Several SAT processes improve water quality during percolation through the unsaturated (vadose) zone (Quanrud et al., 2003) before it is dispersed and diluted in the aquifer (Nema et al., 2001).

SAT is a low cost alternative for wastewater reclamation which does not require much energy and chemical usage, making it suitable for developed and developing countries (Sharma et al., 2008). SAT is defined as a three- component treatment process consisting of the infiltration zone, vadose zone (region of aeration above the water table) and aquifer storage (AWWA-RF, 2001). It 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 zone and saturated zone (aquifer) (Figure 2-2). 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 (geology and hydrogeology) and the operational schedule of the infiltration basins (Harun, 2007; Sharma et al., 2008; NCSWS, 2001).

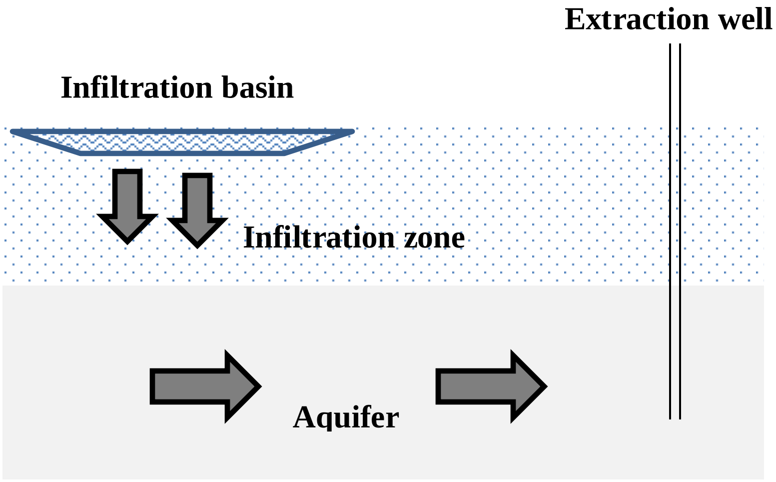


Figure 2-2: Schematic of the soil aquifer treatment (SAT)

Adapted from Fox et al. (2005)

Site characteristics, i.e. local soil, hydrogeology and geology, control the hydraulic conductivity, infiltration rates, bacterial attachment, reaeration rates and adsorption capacity. SAT has been proposed as an alternative to further purified secondary effluents while recharging aquifers. It is important to differentiate between direct injection aquifer recharge and SAT. In direct injection aquifer recharge highly treated effluents are injected into the aquifers for subsequent reuse. In SAT, secondary effluents are allowed to infiltrate the soil until they reach the aquifer, which may take long periods of time. This subjects the secondary effluent to different redox conditions as it moves through the unsaturated and saturate zones. The redox conditions in the unsaturated zone seems to have the most important effect on biological mediated reactions (AWWA, 2001).

The main hydraulic parameters to consider for the design of a SAT are the infiltration rates (R_i), permeability, retention time, and ground water hydrogeology. Infiltration rates are highly affected by the temperature of the reclaimed water since the relationship is inversely proportional to viscosity. For this reason, summer time reclaimed water has lower viscosity and therefore higher infiltration rates than that of more viscous cooler water during the winter time (Bouwer, 2002; Katukiza, 2006). Infiltration rates may vary from 0.3 to 3 m d^{-1} , however, typical systems range from 0.5-1.5 m d^{-1} (Bouwer, 1999). The depth of the water table is also a key factor. The relationship between the depth of the water table and the bottom of the recharge basin with relation to infiltration rates is linearly proportional (Bouwer, 2002). In general, infiltration rates are site specific and there must always be a complete pilot evaluation before large scale implementation is done.

Permeability of the SAT system is dependent on the type of soil. Since high infiltration rates are desired, sites with soils of high permeability should be considered. Hydraulic retention time is also an important factor in SAT for processes such as the biodegradation of organic matter, nitrification and denitrification. Additionally, the ground water table may also be an important hydraulic factor, in that it provides a means of dilution to the reclaimed wastewater before it eventually enters the aquifer. In areas where the water table is too high it will prevent the drying cycle to be effective hence reducing ammonia conversion (Amy and Drewes, 2006).

Processes that promote the growth of algae should highly be avoided since they lead to clogging of the system and reduce the amount of dissolved carbon dioxide found in the water, thus increasing water pH. High pH values further lead to precipitation of calcium carbonate. Precipitated calcium carbonate forms a cement liked surface leading to more clogging and the rate of infiltrated is greatly affected.

2.5.1 Removal of wastewater constituents during SAT

There has not been SAT studies with specific high permeability soils form southwestern Ontario, however, some authors have investigated the performance SAT systems with similar type of soils such as sandy soils. 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. DOC from secondary effluents is largely removed due to biodegradation by the action of microorganisms naturally present in the soils or introduced through engineered systems (Essandoh et al., 2013). An extensive study to investigate the sustainability of SATs undertaken by several universities and organizations in the U.S. (NCSWS, 2001) was conducted using four field sites in Arizona and California with a wide range of specific characteristics. No correlations between the depth of the unsaturated zone and treatment efficiencies were observed, however soil properties affect bacterial attachment, adsorption, infiltration and re-aeration rates. The removal of DOC was found to be dependent on the remaining readily biodegradable carbon after pre-treatment and the majority of it was removed in the top 3 meters of soil to less than 5 mg/l under aerobic and anoxic conditions. Over periods of time longer than 6 months, the majority of trace organic compounds were removed to background levels. Harun (2007) also concluded that concentrations of DOC in SAT effluents were below the average DOC found in drinking water supplies (2.2 mg/L) for long term SAT of both secondary and tertiary influents. Therefore, tertiary treatment prior to SAT may not be needed.

Amy and Drews (2007) investigated the removal of organic matter and trace organic compounds by two SAT facilities in Arizona. The observed removal of DOC was between 50 % to 75 %; accompanied by almost complete elimination of Dissolved Organic Nitrogen (DON). Non-humic compounds were found to be removed over shorter travel times than humic components.

Fox et al. (2005) demonstrated that sustained removal of organic carbon is possible using data collected from simulated and field SAT systems with five different types of soils. Although organic carbon is accumulated at the surface from biological activity, there was no evidence of organic carbon accumulation in soils below a depth of 8 cm. Abel et al. (2012) found high removal of bulk organic matter, nutrients and microorganisms at higher temperatures using primary effluent in a simulated SAT.

High variability of DOC reductions from secondary effluents by SAT has been reported in several studies. This high variability is attributed to the fact that performance of SAT systems is highly dependent of soil characteristics, operation schedules and initial DOC concentrations. Cha et al (2004, 2005) studied the removal of DOC, ammonia, nitrates from secondary effluents using poorly graded sands. They found maximum removals of 60 %, 76% and 7 % respectively. Quanrud et al.(1996) found a 48% removal of DOC using poorly graded sands with an influent concertation of 25mg/L. Idelovitch et al. (2003) and Kanarek and Michail (1996) achieved maximum DOC removals of 74% and 83 % using sandy soils in field studies.

Nitrogen species present in wastewater include different forms of organic and inorganic nitrogen. Organic nitrogen and ammonia are more prevalent in raw wastewater, while nitrates are mostly found in secondary effluents. 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 groundwaters do not meet drinking water standards (AWWA-RF, 1998). Ammonia removal is predominately removed by adsorption into the soils during the wetting cycle followed by subsequent Nitrification during the drying cycle. Nitrate removal in mainly due to denitrification, which requires an adequate carbon source and anaerobic conditions. Nitrate and ammonia removal has also been attributed to anaerobic ammonia oxidation (ANAMMOX), where adsorbed ammonia can serve as an electron donor to convert nitrites into nitrogen gas (Crites et al., 2014).

Nitrogen removal present a challenge to SAT since at concentration in excess of 20 mg/L the nitrogenous oxygen demand cannot be met. Secondary effluents with nitrate concentrations higher than 10 mg N/L will result in incomplete denitrification because of deficient biodegradable organic carbon in secondary effluents (NRC, 2012). Ammonia removal during SAT systems have been reported by several authors which also shows high variability. Using sand and gravel overlain by alluvium, Miller et al.(2006) reported an average ammonia removal of 92.85 % under oxic conditions. Cha et al. (2005) reported 76.42% and 59.04% removal efficiencies for influent concentrations of 12.3 and 8.30 mg/L respectively using poorly graded sands in laboratory scale systems. In a column experiment by Fox et al. (2006) using poorly graded silty sand under anoxic conditions, 50% NO_3-N was removed from a 30 mg/L influent.

Phosphorus removal during SAT is predominately due to adsorption into the soil and chemical precipitation. (Crites et al., 2014). However, other mechanisms such as filtration and microbial uptake also reduce phosphorus concentrations. High PO_4-P removals from previous SAT studies have been reported by various authors. Idelovitch et al.(2003) achieved a 99% removal using sandy soils under oxic/anoxic conditions. Kanarek and Michail (1996) reported a removal efficiency > 99.00% with the use of sandy soils. Although high phosphorous removal has been observed, sustainable long term phosphorous removal cannot be achieved because adsorption is the main removal mechanism and therefore is limited by the adsorption capacity of the soil (Harun, 2007).

Bacteria are removed by filtration, predation, adsorption into the soil. Virus are removed through inactivation and adsorption mechanism (Harun, 2007). However, human enteric viruses have low adsorption to soil and survive longer in the environment (Powelson et al., 1993). Removal efficiency varies depending on the physical and chemical characteristics of the soil, degree of soil saturation and the nature of the microorganisms. Yona (2011) observed a removal of 99% of fecal coliform by filtration. Removal of viruses, is control by sorption and decay, however re-mobilization of attached coliphage has been observed during simulated rain events (Quanrud et al., 2003). Tracer studies also suggest a 7-log reduction of bacteriophage within 100 feet of subsurface travel. Several studies have reported very high removals of bacteria, viruses and protozoa using sandy soils (Betancourt et al., 2014; Castillo et al., 2001; Powelson et al., 1993; Quanrud et al., 2003b)

Removal of emergent contaminants by SAT has been investigated by several authors. Onesios and Bouwer (2012) investigated the removal PPCPs using a laboratory simulation of a SAT system. 10 out of 14 of the supplied PPCPs (biphenylol, p-chloro-m-cresol, chlorophene, 5-fluorouracil, gemfibrozil, ibuprofen, ketoprofen, naproxen, triclosan and valproic acid) were removed by greater than 95% during column passage, while the four other compounds (biosol, p-chloro-m-xylenol, sodium diclofenac, and gabapentin) exhibited poor removals under all tested conditions. He et al (2016) investigated the effects of operating conditions on the removals of 42 different PPCPs using a lab-scale SAT. They found high removal of most PPCPs at HRT of 7 days under saturated condition.

Yoo et al. (2006) reported removal efficiencies at 84% and 98% for EDT (26.9µg/L) and NTA (4.1 µg/L) respectively using poorly graded silty sands with oxic/anoxic conditions. Fox et al. (2006) reported 99 % removal of EDC-17 β-estradiol (200 ng/L), 100 % removal of EDC-estriol (200 ng/L) and 100% removal of EDC-testesterone (200 ng/L) at oxic conditions. 99.9 % removal of EDC-17 β-estradiol (285 ng/L), 99.7 % removal of EDC-estriol (161 ng/L) and 9938 % removal of EDC-testosterone (218 ng/L) at anoxic conditions. Drews et al (2010) reported removal efficiencies of 41 %, 100 %, 100 %, 100%, 99.99 % and 100 % for trace organics such as Primidone (110ng/L), Diclofenac (80ng/L), Ibuprofen (3380ng/L), Ketoprofen (45ng/L), Naproxen (6280ng/L), Fenprofen (35ng/L) and Propyphenazone (20 ng/L) respectively.

Guizani et al (2011) assessed the removal of endotoxin in a laboratory-scale SAT with four different filter materials (fine sand, medium sand, coarse sand and very coarse sand). There results showed that adsorption test data fit to the Freundlich isotherm and were affected by the particle grain size with higher adsorption capacity for fine and medium sand.

SAT for CSOs has not been as extensively investigated as SAT using secondary and tertiary effluents. Reemtsma et al (2000) investigated the removal of heavy metals from CSOs by SAT since urban runoff is common source of Al, Ba, Fe, Pb, and Zn. They found high removals of heavy metals from CSOs by field and laboratory scale SAT systems. Scheurer et al. (2015) investigated the removal of pathogens from CSOs by retention soil filter and found reduction of E. coli, enterococci and staphylococci by 2.7, 2.2 and 2.4 log-units (median values), respectively.

2.5.2 Cost analysis of SAT in comparison with other technologies

The applications of reclaimed water will determine the degree of treatment that is necessary and therefore the capital and operational costs for a specific treatment train. SAT may be a more economical alternative to further treat secondary effluents, however its performance depends on local characteristics such as type of soils, hydrogeology and secondary effluent characteristics, therefore it cannot be implemented everywhere. Land availability is also an important factor, since infiltration basins are required.

Cost-benefit analyses have been completed for wastewater reclamation initiatives around the world which include tangible and non-tangible benefits (Molinos-Senante et al., 2011; Kfouri, 2000; AQUAREC, 2006, NRC,2012). However, a comprehensive cost-benefit analysis of Soil Aquifer Treatment in comparison to other technologies has not been performed.

2.6 References

Abel, C.D.T., Sharma, S.K., Malolo, Y.N., Maeng, S.K., Kennedy, M.D., Amy, G.L.,2012. Attenuation of bulk organic matter, nutrients (N and P), and pathogen indicators during soil passage: Effect of temperature and redox conditions in simulated soil aquifer treatment (SAT). Water. Air. Soil Pollut. 223, 5205–5220.

Amy G. and Drewes J. Soil aquifer treatment (SAT) as a natural and sustainable wastewater reclamation/reuse technology: fate of wastewater effluent organic matter (EfOM) and trace organic compounds. Environmental Monitoring and Assessment. 2007 Jun; 129(1-3):19-26. Epub 2006 Oct 28.

American Water Works Association – Research Foundation (AWWA-RF). Soil Aquifer Treatment for Sustainable Water Reuse. 2001. ISBN 1-58321-113-0.

Asano T., Burton F., Leverenz H., Tsuchihashi R. and Tchobanoglous G. Water Reuse : Issues, Technologies and Applications. Metcalf & Eddy – AECOM. McGraw-Hill. 2007.

AQUAREC, Handbook on feasibility studies for water reuse systems. Development of analysis tools for social, economic and ecological effects of water reuse. www.aquarec.org

Bdour A., Hamdi M. and Tarawneh Z. Perspectives on sustainable wastewater treatment technologies and reuse options in the urban areas of the Mediterranean region. Desalination 237 (2009) 162–174.

Betancourt W., Kitajima, M., Wing A., Regnery J., Drewes J., Pepper I., Gerba C. Assessment of virus removal by managed aquifer recharge at three full-scale operations. 2014. Journal of Environmental science and health. Volume: 49 Issue: 14 Pages: 1685-1692.

Cain Charla. An analysis of direct potable water reuse acceptance in the United States: obstacles and opportunities. Johns Hopkins Bloomberg School of Public Health, April 29, 2011

Castillo, G., Mena, M.P., Dibarrart, F., Honeyman, G., 2001. Water quality improvement of treated wastewater by intermittent soil percolation. Water Sci. Technol. 43, 187–190.

Cha, W., Fox, P., Mir, F. N., and Choi, H. (2004) Characteristic of biotic and abiotic removals of dissolved organic carbon in wastewater effluents using soil batch reactors. Water Environmental Research, 76(130), 130-136.

Cha, W., Choi, H., Kim, J., Cho, J., 2005. Water quality dependence on the depth of the vadose zone in SAT-simualated soil columns. Water Sci. Technol. Water Supply, 5, 17–24.

Chalmers B., Patel M. And Yoder D. Indirect Potable Reuse versus Direct Potable Reuse What’s the Difference? 2011 WateReuse Symposium. Chandler, Arizona.

Claire Kfouri, Water Reuse - Cost Benefit Analysis, The Morocco Example. www.worldbank.org, 2009 (accessed July, 2015).

Crites R., Middlebrooks J., Bastian R and Redd S. Natural Wastewater Treatment Systems, Second Edition. 2014. IWA publishing. CRC press.

Dillon P., Pavelic P., Toze S., Rinck-Pfeifferb S., Martinc R., Knaptond A. and Pidsleye D. Role of aquifer storage in water reuse. Desalination 188 (2006) 123–134.

Essandoh H.M.K., Tizaoui C and Mohamed M.H.A. Removal of dissolved organic carbon and nitrogen during simulated soil aquifer treatment. 2013. Water research 9892.

Dolnicar and Schafer. Desalinated versus recycled water: Public perceptions and profiles of the accepters. Journal of Environmental Management 90 (2009) 888–900.

Exall C., Marsalek J. And Schaefer K. Water Reuse in Canada: Opportunities and Challenges. National Water Research Institute, Environment Canada. In P. Hlavinek et al (eds), Integrated Urban Water Resources Management, 253 – 262. 2006 Canadian Crown. Printed in Netherlands.

Fox, P., Houston, S., Westerhoff, P., Nellor, M., Yanko, W., Rincon, M., Gully, J., Carr, S., Arnold, R., Lansey, K., Quanrud, D., Ela, W., Amy, G., Reihar, M., Drewes, J.., 2006. Advances in soil aquifer treatment research for sustainable water reuse. Awwa Res. Found. Denver,.

Fox, P., National Centre for Sustainable Water S, Foundation AR, United States. Environmental Protection A, 2001a. an Investigation on Soil-Aquifer Treatment for Sustainable Water Reuse.

Fox, P., Nellor, M., Arnold, R., Lansey, K., Bassett, R., Gerba, C., Karpiscak, M., Amy, G., Richard, M., 2001b. An investigation on Soil aquifer treatment for sustainable water reuse. AWWA Res. Found. Am. Water Work. Assoc. USA.

Government of Canada. Canadian Guidelines for Domestic Reclaimed Water for Use in Toilet and Urinal Flushing. 2011. http://healthycanadians.gc.ca/ (accessed August, 2016)

Guizani M., Kato H and Funamizu N. Assessing the removal potential of soil-aquifer treatment system (soil column) for endotoxin. Journal of Environmental Monitoring, 2011, 13, 1716.

Haddad B., Rozin P., Nemeroff C. and Slovic P. The psychology of water reclamation and reuse : Survey findings and research road map. Water Reuse Foundation, 2009.

Hartley T. Public perception and participation in water reuse. Desalination 187 (2006) 115–126

Harun, C.M. (2007) Analysis of multiple contaminants during soil aquifer treatment. UNESCO-IHE MSc thesis No MWI-2007-18.

He, K., Echigo, S. and Itoh, S. Effect of operating conditions in soil aquifer treatment on the removals of pharmaceuticals and personal care products. 2016. Science of the Total Environment. Volume: 565 Pages: 672-681

Idelovitch, E., Icekson-Tal, N., Avraham, O., Michail, M., 2003. The long-term performance of Soil Aquifer Treatment (SAT) for effluent reuse. Water Sci. Technol. Water Supply 3, 239–246.

Jimenez Blanca and Asano Takashi. Water Reuse. An international survey of current practice, issues and needs. 2008. IWA publishing.

Kanarek, A., Michail, M., 1996. Groundwater recharge with municipal effluent: Dan region reclamation project, Israel. Water Sci. Technol. 34, 227–233. doi:10.1016/S0273-1223(96)00842-6

Katukiza, A.Y., 2006. Effects of wastewater quality and process parameters on the removal of organic matter during soil aquifer treatment. Msc Thesis No MWI- 2006-

15, UNESCO-IHE DelftThe Netherlands.The Netherlands.

Kinney C,. Furlong E., Werner S. and Cahill J. Presence and distribution of wastewater-derived pharmaceuticals in soil irrigated with reclaimed water. Environmental Toxicology and Chemistry (February 2006), 25 (2), pg. 317-326.

Lazarova V., Choo K. and Cornel P. 2012. Water-Energy Interactions in Water Reuse. IWA Publishing. London, UK.

McClelland C.G., Linden K., Drewes J., Khan S., Smith J., Raucher B. Water Reuse 2030 Identifying Challenges. 14th Annual Water Reuse & Desalination Conference. 25 May 2010, Tampa Bay, Florida.

Miller G.W. Integrated concepts in water reuse: managing global water needs. Desalination 187 (2006) 65–75.

Miller, J., Ela, W., Lansey, K., Chipello, P. and Arnold, R. 2006. Nitrogen Transformations during Soil–Aquifer Treatment of Wastewater Effluent—Oxygen Effects in Field Studies. J. Environ. Eng. 132, 1298–1306. doi:10.1061/(ASCE)0733-9372(2006)132:10(1298)

Molinos-Senate, Hernandez-Sancho and Sala Garrido. 2011. Cost-benefit analysis of water-reuse projects for environmental purposes: a case study for Spanish wastewater treatment plants. Journal of Environmental Management. Dec:92(12):3091-7.

National Center for Sustainable Water Supply (NCSWS). Investigation on Soil-Aquifer Treatment for sustainable water reuse. Arizona State University. www.eas.asu.edu/~civil/ncsws/NCSWS.html (accessed February 2015)

Onesios K. and Bouwe E. 2012. Biological removal of pharmaceuticals and personal care products during laboratory soil aquifer treatment simulation with different primary substrate concentrations. water research 46-2012-2365-2375.

Powelson, D.K., Gerba, C.P., Yahya, M.T., 1993. Virus transport and removal in wastewater during aquifer recharge. Water Res. 27, 583–590.

Po M.,Kaercher J. and Nancarrow B. Literature review of factors influencing public perceptions of water reuse. CSIRO Land and Water. Technical Report 54/03, December 2003

Public Utilities Board of Singapore (PUB), 2011. NEWater. www.pub.gov.sg (accessed April 11, 2013)

Quanrud, D., Arnold, R., Wilson, L., Gordon, H., Graham, D., Amy, G., 1996. Fate of Organics during Column Studies of Soil Aquifer Treatment. J. Environ. Eng. 122, 314–321.

Quanrud, D.M., Carroll, S.M., Gerba, C.P., Arnold, R.G., 2003a. Virus removal during simulated soil-aquifer treatment. Water Res. 37, 753–762. doi:10.1016/S0043-1354(02)00393-7

Quanrud, D.M., Hafer, J., Karpiscak, M.M., Zhang, J., Lansey, K.E., Arnold, R.G., 2003b. Fate of organics during soil-aquifer treatment: Sustainability of removals in the field. Water Res. 37, 3401–3411. doi:10.1016/S0043-1354(02)00489-X

Rauch-Williams, T., Drewes, J.E., 2006. Using soil biomass as an indicator for the biological removal of effluent-derived organic carbon during soil infiltration. Water Res. 40, 961–8. doi:10.1016/j.watres.2006.01.007.

Reemtsma T., Gnirss R. and Jekel M. Infiltration of Combined Sewer Overflow and Tertiary Treated Municipal Wastewater: An Integrated Laboratory and Field Study on Various Metals. 2000. Water Environment Research, Volume 72, Number 6

Robinson K., Robinson C. and Hawkins S. Assessment of public perception regarding wastewater reuse. Water Science and Technology: Water Supply Vol 5 No 1 pp 59–65. IWA Publishing 2005.

Rock C., Uhlman K., Eden S., Newell S., Westfall E and White M. Survey of public perceptions regarding water reuse in Arizona: Challenges and Opportunities. Maricopa Agricultural Center . Soil, Water, and Environmental Science Department. The University of Arizona. 2008.

Rodriguez C., Van Buynder P., Lugg R., Blair P., Devine B., Cook C. and Weinstein P. Indirect Potable Reuse: A Sustainable Water Supply Alternative. International Journal of Environmental Research and Public Health, 2009, 6, 1174-1209.

Rygaard M., Binning P., Albrechtsen H. Increasing urban water self-sufficiency: New era, new challenges. Journal of Environmental Management 92 (2011) 185e194

Schmidt, C.K., Lange, F.T., Brauch, H.-J., 2007. Characteristics and evaluation of natural attenuation processes for organic micropollutant removal during riverbank filtration. Water Sci. Technol. Water Supply 7, 1–7.

Scheurer M., Hess S., Luddeke F., Sacher F., Gude H., Loffler H. and Gallert C . Removal of micropollutants, facultative pathogenic and antibiotic resistant bacteria in a full-scale retention soil filter receiving combined sewer overflow. Environmental science, processes and impacts. 2015. Volume: 17 Issue: 1 Pages: 186-196.

Sprague J. “Great Wet North? Canada’s Myth of Water Abundance. In Canada” in Eau Canada, Ed. Karen Bakker, UBC Press: 2007.

Sharma S., Harun C. and Amy G. Framework for assessment of performance of soil aquifer treatment systems. Water Science & Technology—WST, 57.6, 2008.

The WABAG group. Windhoek Goreangab Water Reclamation Plant, Namibia. www.wabag.com (accessed on April 11, 2013)

Thirlwell G., Madramotoo C and Heathcote I. Energy-Water Nexus: Energy Use in the Municipal, Industrial and Agricultural Water Sectors. Canada – US Water Conference. Washington D.C. October 02, 2007.

Torcellini P., Long N. and Judkoff R. Technical Report: Consumptive Water Use for U.S. Power Production. National Renewable Energy Laboratory. 2003.

Tchobanoglous, G., Burton, F.L., Stensel, H.D., Eddy, M.&, 2003. Wastewater engineering :treatment and reuse, McGraw-Hill series in civil and environmental engineering. McGraw-Hill, Boston.

Toze s. Water reuse and health risks — real vs. Perceived. Desalination 187 (2006) 41–51

United Nations Educational, Scientific and Cultural Organization (UNESCO). The United Nations World Water Development Report. Managing Water under Uncertainty and Risk. 2012. Paris, France.

U.S. Environmental Protection Agency (EPA). Guidelines for water reuse. EPA/600/R-12/618, September 2012.

WCED (1987) Report of the World Commission on Environment and Development: Our Common Future. UN Documents. http://www.un-documents.net/wced-ocf.htm

Westerhoff, P., Pinney, M., 2000. Dissolved organic carbon transformations during laboratory-scale groundwater recharge using lagoon-treated wastewater. Waste Management 20, 75–83.

Wintgens T., Salehi F., Hochstrat R. and Melin T. Emerging contaminants and treatment options in water recycling for indirect potable use. Water Science & Technology—WST, 57.1, 2008.

World Health Organization (WHO). Progress on Sanitation and Drinking Water. 2013. http://apps.who.int/iris/bitstream/10665/81245/1/9789241505390_eng.pdf (accessed August 2016)

Yoo, H.H., Miller, J., Lansey, K., Reinhard, M., 2006. EDTA, NTA, Alkylphenol Ethoxylate and DOC Attenuation during Soil Aquifer Treatment. J. Environ. Eng. 132, 674–682.

Chapter 3

3. Water reuse perceptions of students, faculty and staff at Western University, Canada

(Published in the Journal of Water Reuse and Desalination in 2015)

3.1 Introduction

Achieving sustainable water resources management around the globe is a complex task, with unique challenges to every specific region. These challenges include physical water scarcity, economic water scarcity, water quality degradation and socio-political circumstances among others. Fresh water only constitutes 3 percent of the total amount of water on the planet. And out of this 3 percent, 99 percent is locked up in icebergs, glaciers and underground (Brooymans, 2011). Global water resources are already under increasing pressure from rapidly growing demands for agriculture, production of energy, industrial uses and human consumption. Additionally, global climate change is expected to exacerbate current and future stresses on water resources from population growth and land use, and increase the frequency and severity of droughts and floods (UN, 2012).

Reducing water consumption through water conservation strategies and technological advances and searching for new water sources are the main forms of reducing the pressure that results from physical water scarcity. New water sources may include the recovery of rain and stormwater runoff, desalination of seawater or brackish groundwater, on-site grey water reuse and the reclamation of municipal wastewater effluents (NRC, 2012). Wastewater reclamation is becoming an increasingly important alternative for achieving sustainable water resources management in many regions of the world. It is the process of treating wastewater to high quality standards to make it suitable for reuse. Depending of the level of treatment, reclaimed wastewater may be utilized for potable or non-potable applications.

The main factors driving water reclamation projects around the world have been identified to include lack of water availability, high levels of local water demand, the need for reliable sources of water, the protection of aquatic environments and stringent restrictions on effluent disposal (Jimenez and Asano, 2008; Exall et al., 2006). The highest levels of wastewater reclamation take place in regions suffering from water scarcity, such as in the Middle East, Australia, the Mediterranean and the south western United States (Exall et al., 2006). Agriculture is by far the most important reuse option in terms of volume, basically because it accounts for 70% of total water withdrawals for all sectors/human uses (UNESCO, 2012).

Urban wastewater reclamation can be classified into non-potable, indirect potable and direct potable reclamation. Non-potable uses include irrigation, nature restoration (environmental flows), household toilet flushing and industrial process water. Indirect potable reclamation is the process of supplementing natural water bodies utilized as drinking water supplies by the addition of treated wastewater. Direct potable reclamation is the introduction of reclaimed water directly into the potable water supply distribution system. Additionally, some authors make a distinction between intended and unintended, indirect potable reuse (Wintgens et al., 2008; Rygaard et al., 2011). Unintended (de-facto) indirect potable reuse occurs along major river catchments around the world, where the drinking water supplies are influenced by wastewater discharges by upstream users, while intended indirect potable reuse includes applications such as aquifer and surface water reservoir recharge.

Municipal wastewater reclamation in Canada has been generally conducted on a small scale or experimental basis, mainly for golf course, urban landscape and agricultural irrigation. Industrial wastewater recycling is a more common practice, where approximately 40 % of the total water usage is recycled (Exall et al., 2006). National guidelines for wastewater reuse are limited to the use of domestic reclaimed water for use in toilet and urinal flushing (HC, 2010). Additionally, some guidelines and/or regulations for wastewater reclamation have been developed at the provincial level by British Columbia, Alberta, Saskatchewan, Manitoba and Prince Edward Island (CMHC, 2005). The lack of interest and legislated support for water reclamation in Canada may be driven by the general belief that Canada is a water rich country and its inhabitants do not need to worry about water shortages. However, although Canada has 20% of the world's total freshwater resources, only 7 % is renewable. Furthermore, 60 % of this renewable water supply flows north to the Arctic Circle, making it unavailable for the majority of Canadians that resides along its border with the United States (Environment Canada, 2013). Freshwater in Canada is not an unlimited resource and is already under pressure in some areas of the country due to population growth, changing climatic conditions and excessive extraction by agriculture and industry.

Public acceptance and trust of consumers in the quality of reclaimed water is considered by many to be the most important factor determining the outcomes of water reclamation projects. A major psychological barrier to using reclaimed wastewater is its association with raw sewage, which creates discomfort in the majority of people. For this reason, wastewater reclamation advocates prefer to use the term “re-purified water” instead (Po et al., 2003). A study by the Water Reuse Foundation in which 2,695 people were surveyed in five U.S. cities, some of which are experiencing fresh water shortages, showed that reclaimed wastewater is less likely to be rejected if it has been certified as safe by scientists, has been highly processed, and or has been in contact with natural systems such as aquifers and rivers for some time (Haddad et al., 2009). Additionally, several studies (Table 3-1) conducted during the last decade have shown a higher degree of public acceptance of reclaimed water applications that do not involve close personal contact (such as industrial uses, lawn irrigation, firefighting, car washing and agricultural uses). The use of reclaimed water for applications involving drinking or close personal contact, where there is risk of human ingestion, is less acceptable. Only one study in water reuse perceptions has been previously undertaken in Canada, which was commissioned by the Lake Simcoe Region Conservation in Ontario.

Publication	Author(s)	Location	Year
Water resources and wastewater reuse: perceptions of students at the Ohio State University campus	Sridhar Vedachalam and Karen Mancl	United States (Columbus, OH)	2010
Survey of public perceptions regarding water reuse in Arizona	Rock et al.	United States (AZ)	2012
Stakeholder/public attitudes towards reuse of treated wastewater	Ogilvie, Ogilvie & Company Lake Simcoe Region Conservation	Canada (Ontario, Lake Simcoe watershed)	2010
The psychology of water reclamation and reuse	Haddad et al. Water Reuse Foundation	US (Eugene, OR; Philadelphia, PA; Phoenix, AZ; San Diego, CA; San Jose, CA)	2009
Desalinated versus recycled water: Public perceptions and profiles of the acceptors	Sara Dolnicar and Andrea Schäfer	Australia	2009
Assessment of public perception regarding wastewater reuse	Robinson et al.	United States (South East)	2005

Table 3-1: Published studies on public perceptions of waster reuse

The goal of the present research is to study the perceptions of students, faculty and staff at Western University, London, Ontario Canada, about the reuse of treated wastewater for potable and non-potable applications. This survey is part of a broader research project investigating the potential for wastewater reclamation and purification in a high water demand region, such as Southwestern Ontario.

3.2 Study site

Western University (formerly The University of Western Ontario), located in London, Ontario, has a community of over 30,000 people: 21,801 undergrad students, 4,770 graduate students, 2,461 full time staff and 1,408 faculty members (UWO, 2013). The City of London is located in Southwestern Ontario with an estimated population of 506,400 in 2015 (SC, 2016). Potable water in the City of London is primarily extracted from 2 sources: Lake Huron and Lake Erie (See Figure 3-1). Additionally, a network of 7 groundwater wells from an unconfined overburden sand aquifer and a confined overburden sand and gravel aquifer are maintained as back up for emergency situations (City of London, 2014; UTRCA, 2011). Wastewater is treated by six wastewater treatment plants operated by the City and discharged into the Thames River (City of London, 2014). The Thames River, which extends for 273 km, flows into the Lake St. Clair. It is important to note that Lake St. Clair is part of the Lake Erie basin. Therefore, unintended (de-facto) indirect potable reuse is already part of the daily lives of the inhabitants of Southwestern Ontario.

Figure 3-1. London, Ontario and surrounding water bodies.

Source: DMTI Spatial (2012)

3.3 Methods

An on-line survey was created to investigate the perceptions of students, staff and faculty at Western University regarding wastewater reclamation. The survey was composed of 14 questions divided into 3 sections and included a schematic explanation of a generic wastewater reclamation process. The first section included demographics of the participants, the second section focused on general knowledge regarding water consumption and treatment, and the third section focused on the perception on wastewater reclamation (see Table 3-2). After the survey was approved by the University's Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB), an invitation to participate in the on-line survey was launched and sent by e-mail to students, faculty and staff on the main campus. The survey was hosted on a third party website (www.surveygizmo.com), which permitted the participants to complete the survey on-line in a confidential manner. The raw data were subsequently retrieved at the completion of the survey (after 3 months) for analysis. A total of 432 participants completed the on-line survey from September 15 to December 15, 2013. Fifty two (52) responses were not considered in the analysis because of incomplete answers to some of the questions. The remaining 380 responses allowed for an analysis with a confidence level of 95% and a margin of error of 5%. Statistical analysis was performed using the IBM Statistical Package for the Social Sciences (SPSS), released 2013, version 22.

Questions	Answers
Section 1	
1. Gender	Open-ended question (Tab: Female, Male, Other)
2. What is your occupation at Western University?	Open-ended question (Tab: Undergrad, Graduate, Staff , Faculty)
Section 2	
3. Compared to the world daily average domestic water use, how	a. About the same b. Twice as much c. Three times as much d. Four times as much

much water do you think Canadians use?	
4. Which of the following statements do you agree more with?	a. Fresh water in Canada is an abundant and renewable resource, therefore we don't have to worry about how much we use and/or pollute. b. Freshwater is Canada is not as abundant as we think it is, mainly because most of our fresh water is not renewable. c. Water is a scarce resource in Canada
5. Where does the water you use at home come from?	a. The Great Lakes b. The Thames river c. A ground water well d. Other e. Don't know
6. Who takes care of the wastewater (dirty water) from your home?	a. The municipal sewage treatment system b. A septic tank c. Other d. Don't know
7. After the wastewater is properly treated, where is it released to?	a. The Great Lakes b. The Thames River c. The ground d. Other e. Don't know
8. Please indicate how familiar you are with the following terms:	a. Potable water b. Non-potable water c. Stormwater d. Grey water e. Black water f. Wastewater g. Recycled water h. Reclaimed water
Section 3	
9. Do you think undertaking water reclamation projects as an alternative source of water in southwestern Ontario would be a good idea?	a. Yes b. No c. Unsure
10. What specific uses for reclaimed water would be acceptable or not acceptable to you? Assume the reclaimed water has been certified	**a. Acceptable** **b. Acceptable only under extreme drought conditions** **c. Not acceptable**

as safe by a panel of water experts and has a good taste.	a. Drinking b. Bathing c. Cooking d. Laundry e. Household cleaning f. Food crops irrigation g. Non-food crops irrigation h. Vegetables irrigation i. Golf courses irrigation j. Landscape irrigation k. Fire fighting l. Street cleaning m. Car washes n. Public toilets flushing o. Snow making p. Public swimming pools q. Cooling power plants r. Industrial uses s. Wetlands restoration t. Aquifer recharge
11. Which of the following do you consider a trustworthy source of information on the safety of reclaimed water?	**a. Very trustworthy** **b. Somewhat trustworthy** **c. Not trustworthy** **d. Don’t know**
	a. A private consultant hired by the water treatment facility b. The staff at the water treatment facility c. A qualified university professor d. The provincial government e. The federal government f. The municipality g. The media h. The regional health unit i. The internet
12. How would the following scenarios change your acceptability level of reclaimed water that has been certified as safe by a panel of water experts?	**a. High increase** **b. Slight increase** **c. No increase** **d. Decrease**
	a. The reclaimed water only includes stormwater (rain and snowmelt) b. The reclaimed water only includes storm water and grey water (laundry, dishwashing, and bathing). It does not include toilet flushing.

	c. After the treated wastewater leaves the treatment plant, the water percolates through the soil into the underground aquifer where it mixes with the "natural" aquifer water. After a period of 6 months the water is pumped back and re-treated for human consumption. d. After the treated wastewater leaves the treatment plant, the water is pumped into a lake where it mixes with the "natural" lake water. After a period of 6 months the water is pumped back and re-treated for human consumption. e. After the treated wastewater leaves the treatment plant, the water is pumped into a river where it mixes with "natural" river water. After the water travels for 10 km, it is pumped back and re-treated for human consumption.
13. Do you agree/disagree with the following statements:	**a. Strongly Agree** **b. Agree** **c. Neither agree nor disagree** **d. Disagree** **e. Strongly disagree**
	a. As long as reclaimed water in a drinking water supply is safe, I would rather not know the details. b. If the benefits to the environment are extensive, I would support water reclamation initiatives as long as it is safe for humans. c. Natural water from lakes, rivers and aquifers are of higher quality than reclaimed water from the treatment plant. d. It is important that the reclaimed water goes back into the natural environment before it is reused. e. There is much scientific/technological uncertainty regarding the removal of chemicals such as pharmaceuticals from reclaimed water and the long-term effects on human health from

	exposure to these contaminants are not known. f. As long as reclaimed water is cheaper than other sources of water, I would support water reclamation initiatives as long as it is safe for humans.
14. Do you have any comments regarding water reclamation?	**Open-ended question**

Table 3-2: Survey Questions

3.4 Results and discussion

3.4.1 Section 1

Out the 432 respondents, 221 (51.2%) were female and 208 (48.1%) were male, which is comparatively close to the number of females and males of the Western University community. Students accounted for 63.8% of the respondents, while faculty and staff accounted for 17.4% and 18.7%, respectively. Furthermore, among the student respondents, 47% were undergraduate students and 53% were graduate students. Therefore, the survey responses show an under-sampling of undergraduate students and an over-sampling of graduate students, faculty and staff. This is consistent with the results of a similar survey undertaken at Ohio State University Campus (Vedachalam and Mancl, 2010) where graduate and older students were more likely to respond. Therefore, post stratification weights were applied to the survey results to make the responses more representative of the university population in terms of occupation. Table 3-3 shows the proportion of respondents and the university community demographics in terms of occupation, and the post-stratification weights applied to the data.

	Survey respondents (%)	Western University (%)	Weight
Undergrad Student	30.1	71.8	2.39
Graduate Student	33.7	15.5	0.46
Faculty	17.4	8.1	0.47
Staff	18.7	4.6	0.25

Table 3-3: Occupation proportions and weights

Tests of independence between "occupation" (Undergraduate, Graduate, Staff and Faculty) and the rest of the survey questions were performed using the Chi Square test. Whenever there were cells with an expected count less than 5, Fisher's Exact test was used. If the null hypothesis was rejected ($p<0.05$), the strength of association was measured by Cramer's V coefficient. The tests' independence showed that answers to the majority of the questions were not significantly dependent ($p>0.05$) on the occupation of the respondent. Only responses to question 8a and 8b were significantly dependent on the respondent's occupation ($p<0.05$). Nevertheless, the strength of association was weak in both cases. Table 4 shows the results of test of independence for questions 8a and 8b.

Survey question	Cramer's V	Exact Sig. (2-sided)
8a	0.131	0.35
8b	0.146	.009

Table 3-4. Strength of association of questions significantly dependent on occupation

3.4.2 Section 2

The first question of the second section (Q3) was regarding knowledge of average domestic water usage by Canadians. Average daily residential water usage in Canada is currently

251 liters per capita (Statistics Canada, 2013). Therefore, Canadians consume approximately 2 times the average daily global domestic water use (SASI Group and Newman, 2006). If all uses are included, Canadians consume approximately 3 times the world average. Twenty four percent (24%) of the university community answered correctly that average daily domestic water usage by Canadians is approximately twice the global average. Only 9 % of the university community believes domestic water usage by Canadians is about the same as the world average. The remaining 67% of the university community believes Canadians use more than twice (3 or 4 times) the average daily global domestic water. The second question of this section (Q4), regarding fresh water availability was answered correctly by 92% of the university community. The third question of this section (Q5) was concerned with knowledge about the source of domestic potable water consumption. Fifty percent (50%) of the university community answered correctly that their drinking water comes from the Great Lakes. Approximately 10.3 % responded that their drinking water comes from a ground water well, which is only correct if they reside outside of London in a region that depends on ground water. About 5.5 % of the university community responded that their drinking water source is the Thames River, which is definitely incorrect, and 3.5 % responded that their drinking water comes from a source not stated in the survey. An astonishing 30.7 % of the university community did not know where their drinking water came from. The fourth question of section 2 (Q6) was answered correctly by 80.3 % of the university community. Some 9.2 % responded that wastewater is treated by a septic tank, which is only correct if they reside in a rural area, and 10.5% of the university community did not know who took care of domestic wastewater. The fifth question of section 2 (Q7) was concerned with knowledge about the discharge of treated municipal wastewater. Exactly 26.9% of the respondents answered correctly that treated wastewater effluent is discharged into the Thames River, and 23.4%, 5.2 % and 6.7% of the respondents believed treated wastewater is released to the Great Lakes, underground or other location not mentioned in the survey, respectively. Nearly forty percent (39.7%, precisely) of respondents did not know where treated wastewater was released to. The sixth question of section 2 (Q8) was regarding familiarity with terms broadly used in the water resources management field. Questions 8a and 8b were significantly dependent on the occupation of the respondent. Responses to question 8a,

which asked about familiarity with the "potable water" term, shows that 93 % of the faculty, 85 % of graduate students, 72 % of the staff and 69 % of undergraduate students know what it means. Similarly, question 8b, which asked about familiarity with the term "non-potable water", shows that 93 % of the faculty, 86 % of graduate students, 67 % of the staff and 68 % of undergraduate students know what it means. Responses to questions 8c to 8h were significantly independent of the occupation of the respondent. The percentage of the university community that knows what the following terms mean are: stormwater (78.5%), grey water (39%), blackwater (22.7%), wastewater (80.5%), recycled water (68.1%) and reclaimed water (30.4%). Figures 3-2 to 3-9 show a summary of the responses to section 2 of the survey.

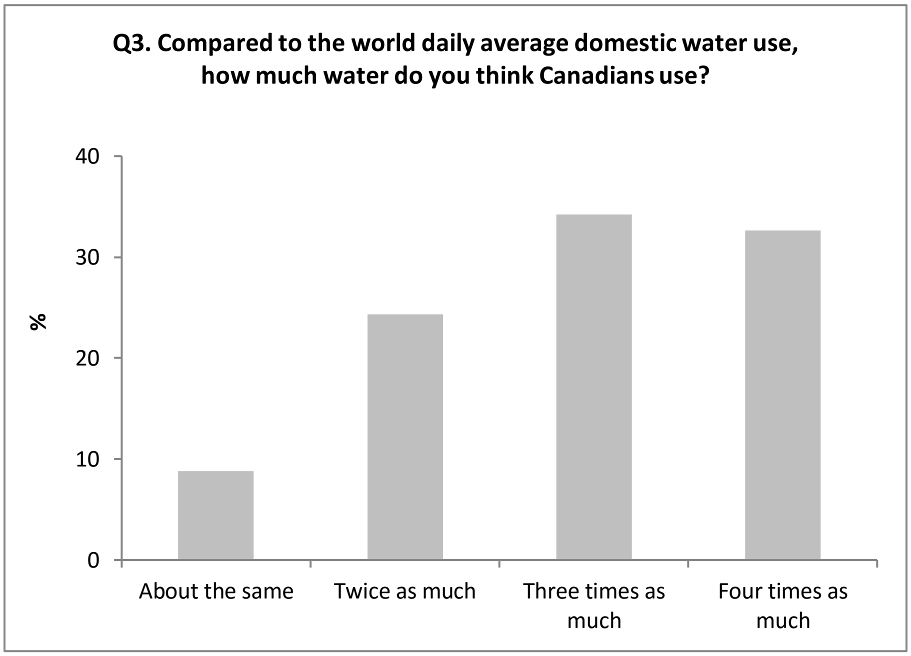


Figure 3-2: Question 3 - survey

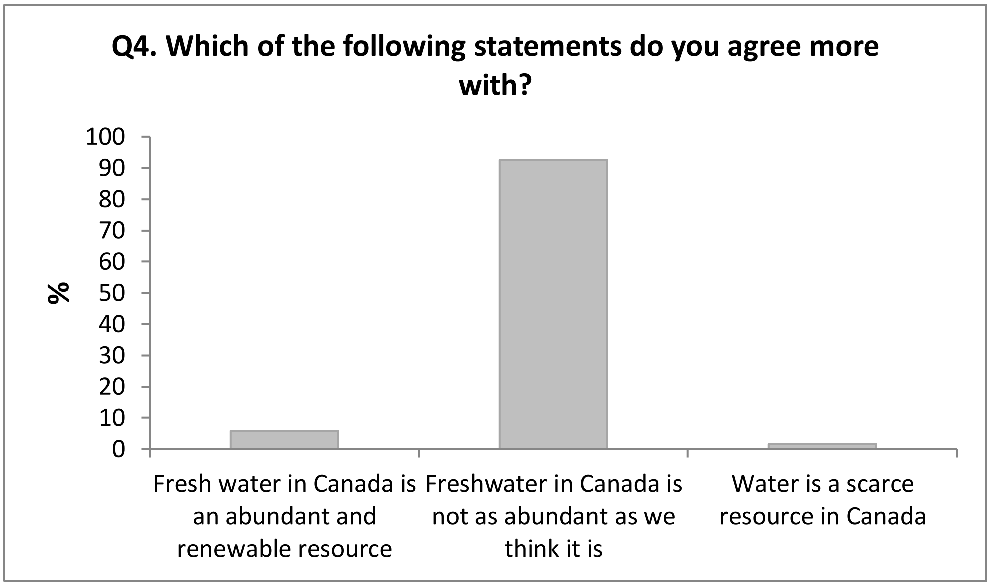


Figure 3-3: Question 4 - survey

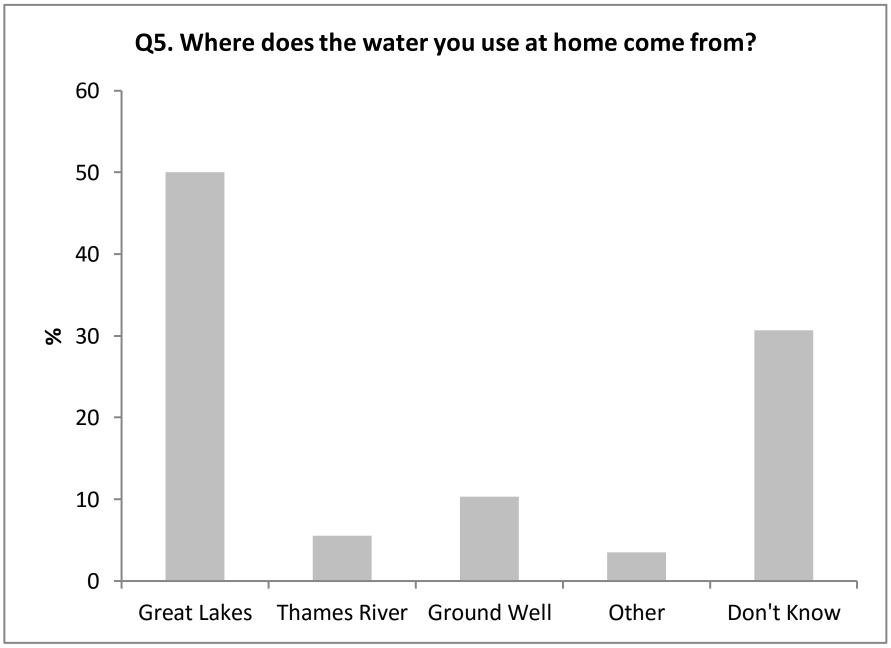


Figure 3-4: Question 5 - survey

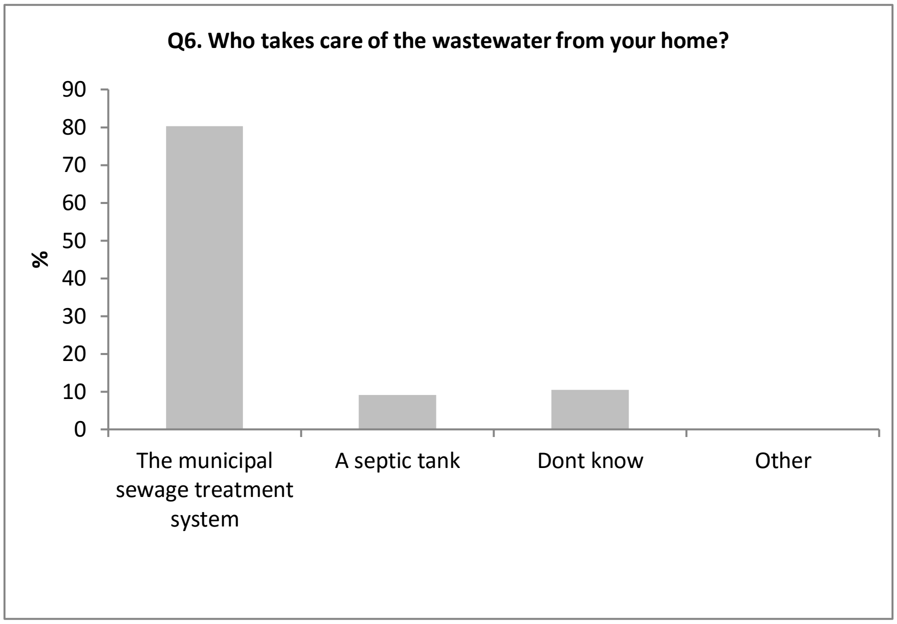


Figure 3-5: Question 6 -survey

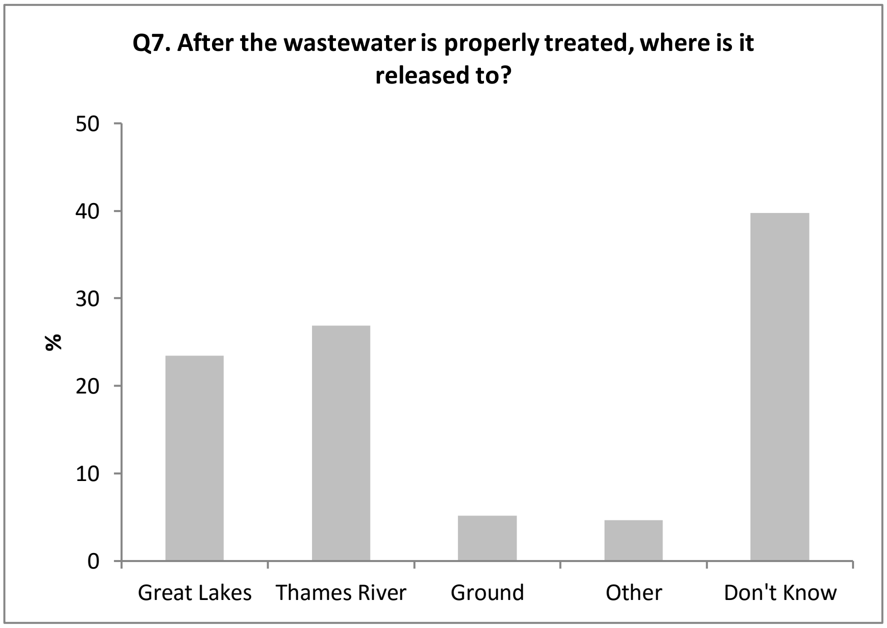


Figure 3-6: Question 7 - survey

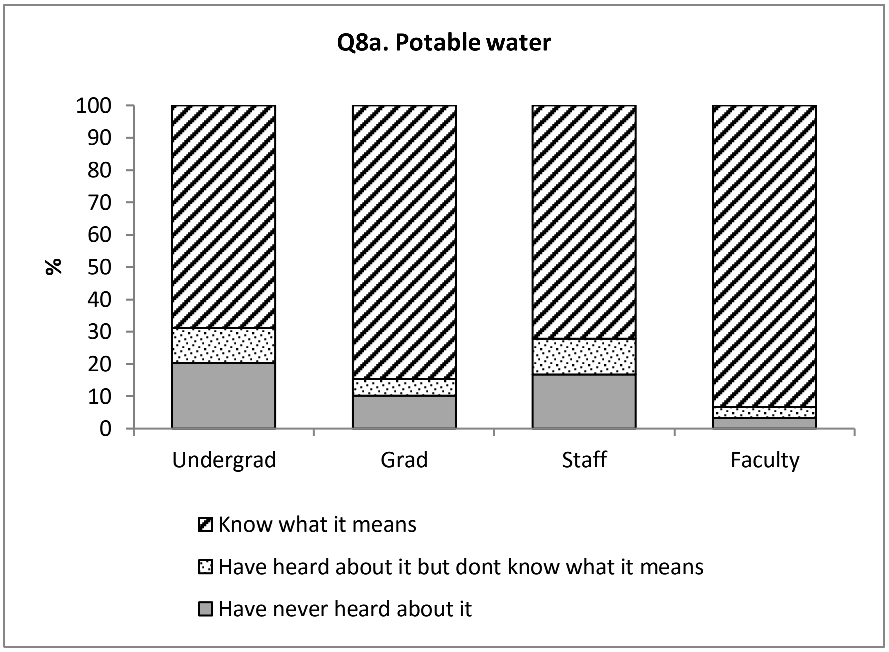


Figure 3-7: Question 8a - survey

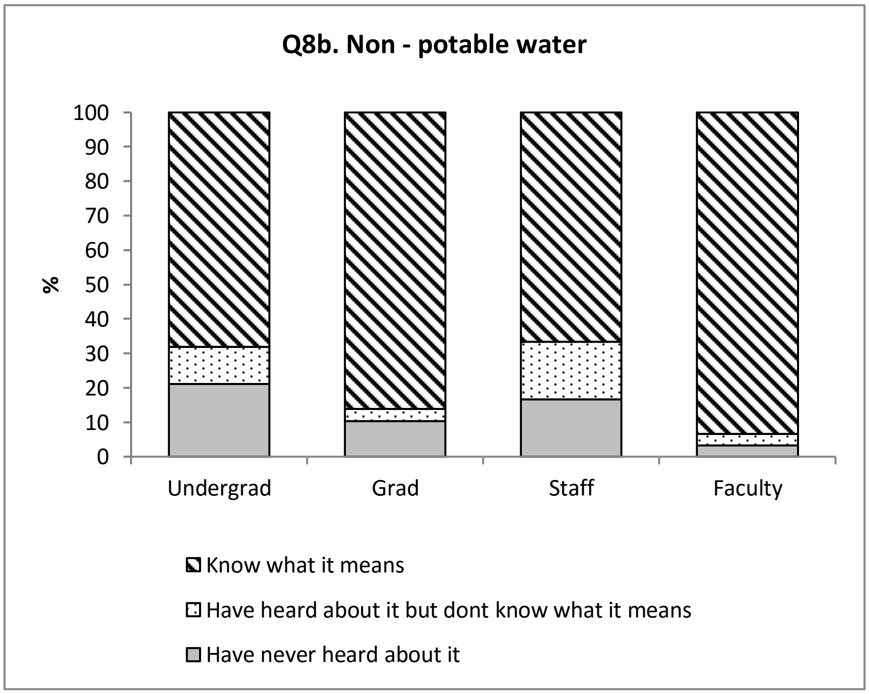


Figure 3-8: Question 8b - survey

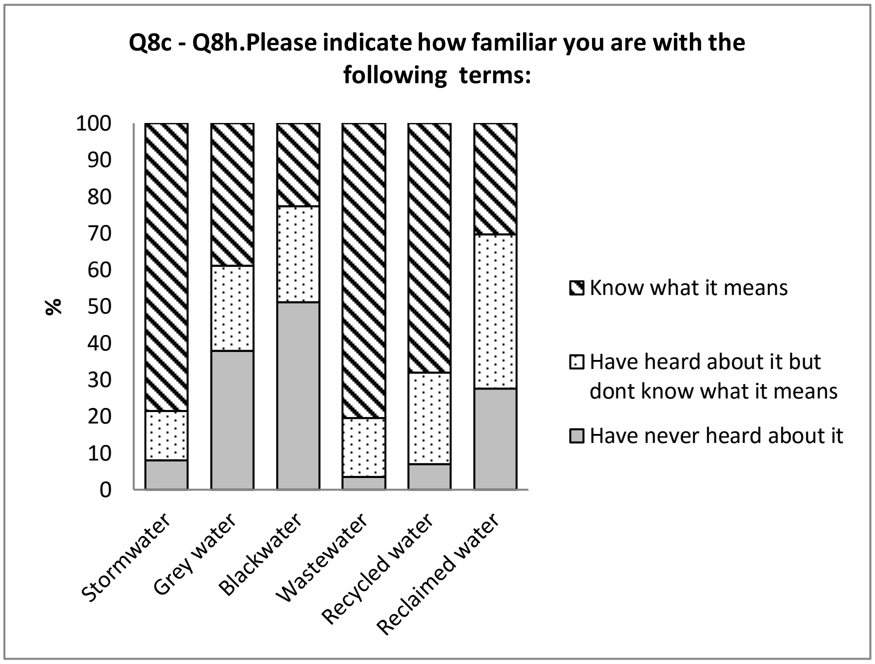


Figure 3-9: Question 8c – 8h - survey

3.4.3 Section 3

Section 3 of the survey, which was concerned with perceptions about wastewater reclamation, comprised 6 questions (Q9- Q14). Five of these questions were categorical and one was open ended. To the first question of this section (Q9), which asked the participants whether or not they thought undertaking water reclamation projects as an alternate source of water in southwestern Ontario was a good idea, 75.8 % of respondents considered it a good idea; 21.6% was unsure about it and 2.5 % thought it was not a good idea. Question 10, asked about the acceptability of specific uses for reclaimed wastewater. Responses show that the closer the reclaimed wastewater is to human contact or ingestion, the lower is its acceptability. Table 3-5 summarizes the responses to question 10.

	Acceptable %	Acceptable only under extreme drought conditions %	Not acceptable %
Drinking	42.1	34.3	23.6
Cooking	51.1	28.7	20.3
Public Swimming pools	63.6	26.2	10.3
Bathing	67.2	23.5	9.3
Food crops irrigation	72.9	21.6	5.6
Vegetables irrigation	73.5	20.5	5.9
Aquifer recharge	81.8	14.3	3.9
Laundry	81.9	10.3	7.9
Snow making	82.8	8.3	8.9
Household cleaning	85.9	8.0	6.1
Wetlands restoration	85.9	10.6	3.5
Non-food crops irrigation	86.0	9.8	4.2
Industrial uses	89.6	4.0	6.4
Landscape irrigation	90.3	4.5	5.2
Golf courses irrigation	90.4	3.6	6.0
Car washes	91.2	3.2	5.6
Street Cleaning	92.3	1.5	6.2
Cooling power plants	92.7	3.8	3.5
Public Toilets Flushing	92.9	1.5	5.6
Fire fighting	94.8	3.3	1.9

Table 3-5: Acceptability of specific uses for reclaimed wastewater.

Responses to question 11, which was concerned with trustworthy sources of information about the safety of reclaimed wastewater, show that the university community considers university professors and the regional health unit to have the highest level of trustworthiness among the given options. The internet and the media were considered the less trustworthy sources of information. Table 3-6 summarizes the responses to question 11.

	Very trustworthy %	**Somewhat trustworthy** %	**Not trustworthy** %	**Don't know** %
The media	1.7	31.9	60.5	5.8
The internet	2.2	36.3	53.5	8.0
The municipality	22.6	60.1	12.7	4.7
A private consultant hired by the water treatment facility	22.9	56.7	16.6	3.8
The federal government	24.7	55.1	16.8	3.3
The provincial government	25.3	59.3	12.2	3.2
The staff at the water treatment facility	32.3	55.6	9.1	3.0
The regional health unit	61.6	33.5	2.0	2.9
A qualified university professor	64.0	31.9	2.3	1.9

Table 3-6: Trustworthiness on information regarding the safety of reclaimed wastewater.

Question 12, which considers changes in the level of acceptability of reclaimed wastewater under different scenarios, shows that acceptability considerably increases if the reclaimed water only includes stormwater and/or grey water. If "high increase" and "slight increase" are combined, the increment of acceptability of the proposed scenarios would rank as (highest to lowest): 1- The reclaimed water only includes stormwater , 2 - The reclaimed water only includes storm water and grey water, 3 – The reclaimed water is used for aquifer recharge before use, 4 - The reclaimed water is mixed with natural lake water before use and 5 - The reclaimed water is mixed with natural river water before use. Table 3-7 summarizes the responses to question 12.

	High increase %	**Slight increase %**	**No increase %**	**Decrease %**
12a	41.5	32.0	26.4	0.0
12b	19.3	39.9	36.7	4.1
12c	27.1	29.2	39.0	4.6
12d	15.3	32.9	43.8	8.0
12e	11.4	28.2	51.8	8.6

a. The reclaimed water only includes stormwater (rain and snowmelt)
b. The reclaimed water only includes storm water and grey water (laundry, dishwashing, and bathing). It does not include toilet flushing.
c. After the treated wastewater leaves the treatment plant, the water percolates through the soil into the underground aquifer where it mixes with the "natural" aquifer water. After a period of 6 months the water is pumped back and re-treated for human consumption.
d. After the treated wastewater leaves the treatment plant, the water is pumped into a lake where it mixes with the "natural" lake water. After a period of 6 months the water is pumped back and re-treated for human consumption.
e. After the treated wastewater leaves the treatment plant, the water is pumped to a river where it mixes with "natural" river water. After the water travels for 10 km, it is pumped back and re-treated for human consumption.

Table 3-7. Acceptability of reclaimed water that has been certified as safe by a panel of water experts under different scenarios

Question 13 asked the participants if they agree or disagree with a group of statements regarding wastewater reclamation. The statement with the highest level of agreement (90.8%) by the university community was "if the benefits to the environment are extensive, they would support water reclamation initiatives as long as it is safe for humans". The statement with the lowest level of agreement (25.5%) by the university community was "Natural water from lakes, rivers and aquifers are of higher quality than reclaimed water from the treatment plant". Table 3-8 summarizes the responses to question 13. Figures 3-10 to 3-14 show a graphical summary of question 9 to 13.

	Strongly Agree (%)	**Agree (%)**	**Neither agree nor disagree (%)**	**Disagree (%)**	**Strongly disagree (%)**
13a	14.3	29.1	17.9	23.1	15.6
13b	61.0	29.9	6.1	2.9	.2
13c	5.0	20.4	48.4	22.6	3.5
13d	9.4	21.3	47.1	18.1	4.1
13e	19.8	40.2	32.7	6.2	1.2
13f	10.6	32.3	36.5	14.2	6.3

a. As long as reclaimed water in a drinking water supply is safe, I would rather not know the details.
b. If the benefits to the environment are extensive, I would support water reclamation initiatives as long as it is safe for humans.
c. Natural water from lakes, rivers and aquifers are of higher quality than reclaimed water from the treatment plant.

d. It is important that the reclaimed water goes back into the natural environment before it is reused.
e. There is much scientific/technological uncertainty regarding the removal of chemicals such as pharmaceuticals from reclaimed water and the long-term effects on human health from exposure to these contaminants are not known.
f. As long as reclaimed water is cheaper than other sources of water, I would support water reclamation initiatives as long as it is safe for humans.

Table 3-8: University community level of agreement/disagreement with different statement regarding water reclamation.

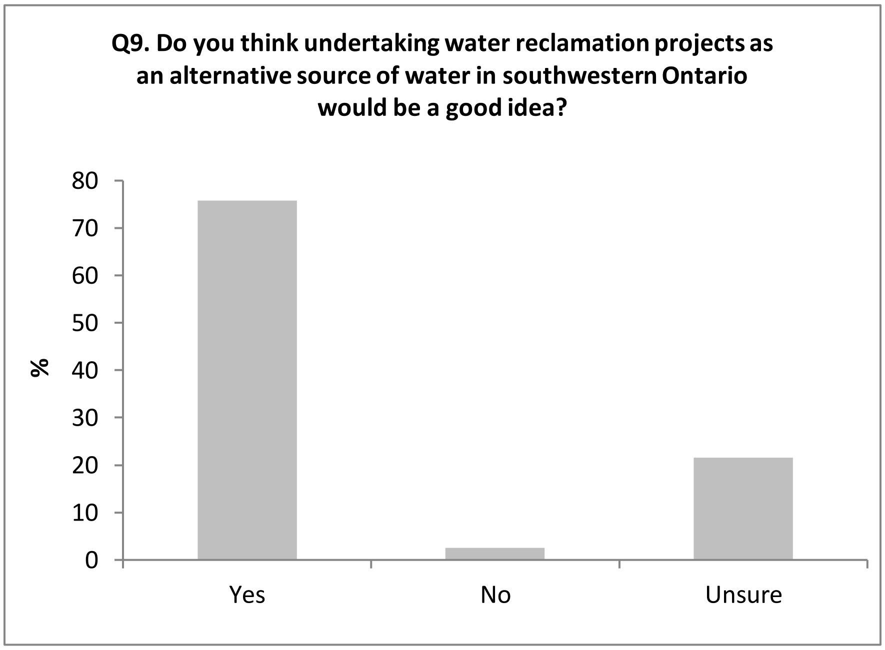


Figure 3 -10: Question 9 - survey

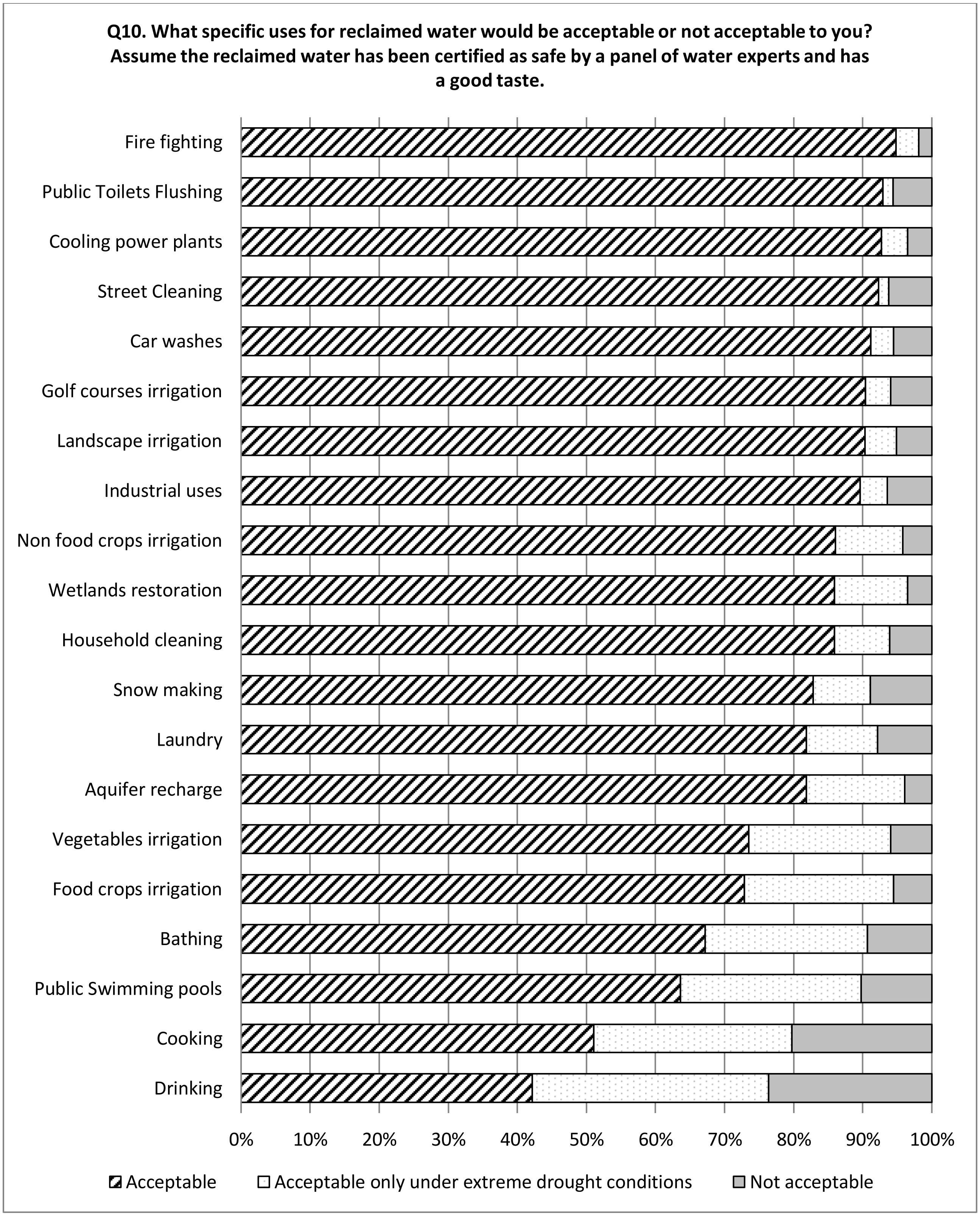


Figure 3-11: Question 10 - survey

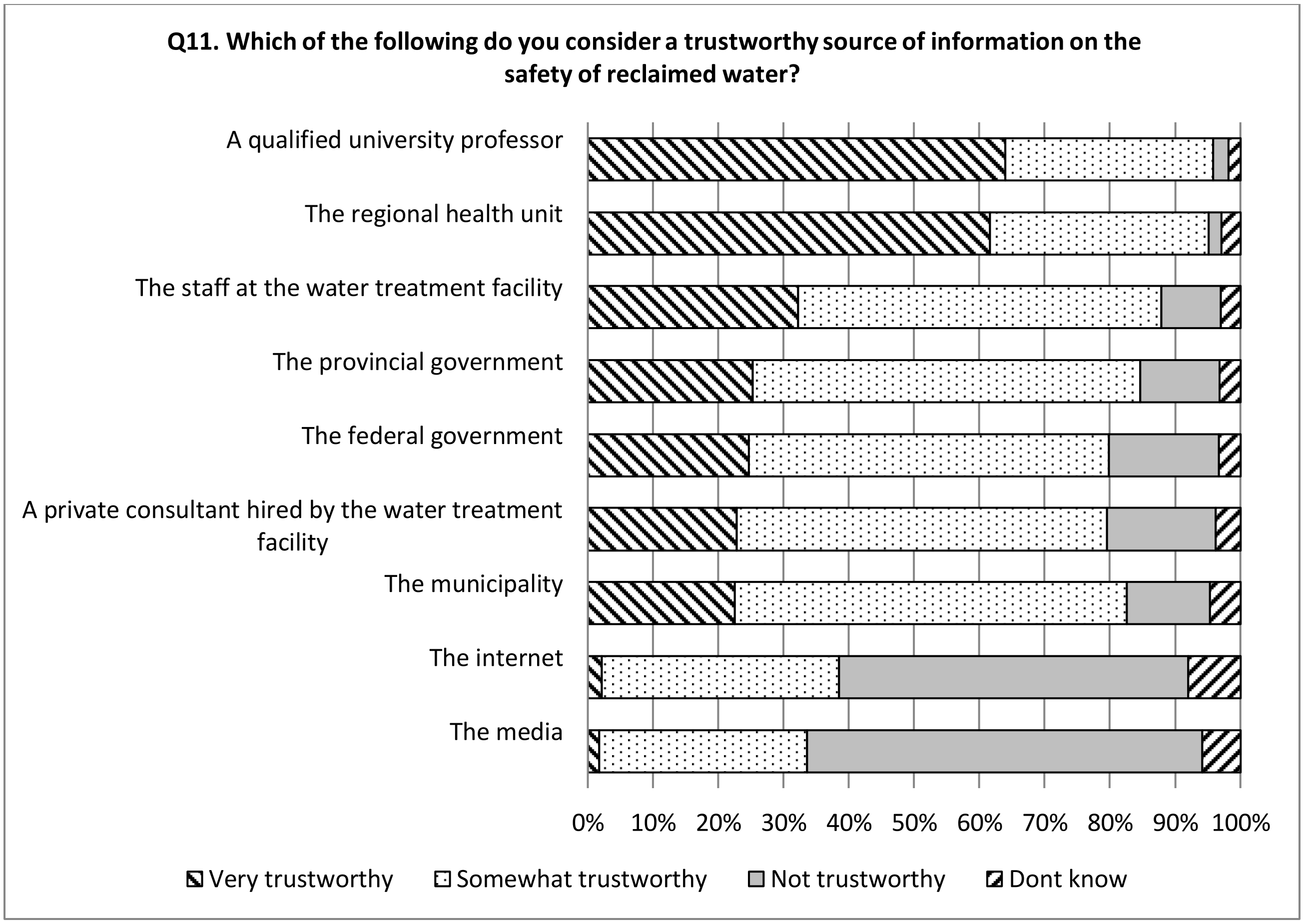


Figure 3-12: Question 11 - survey

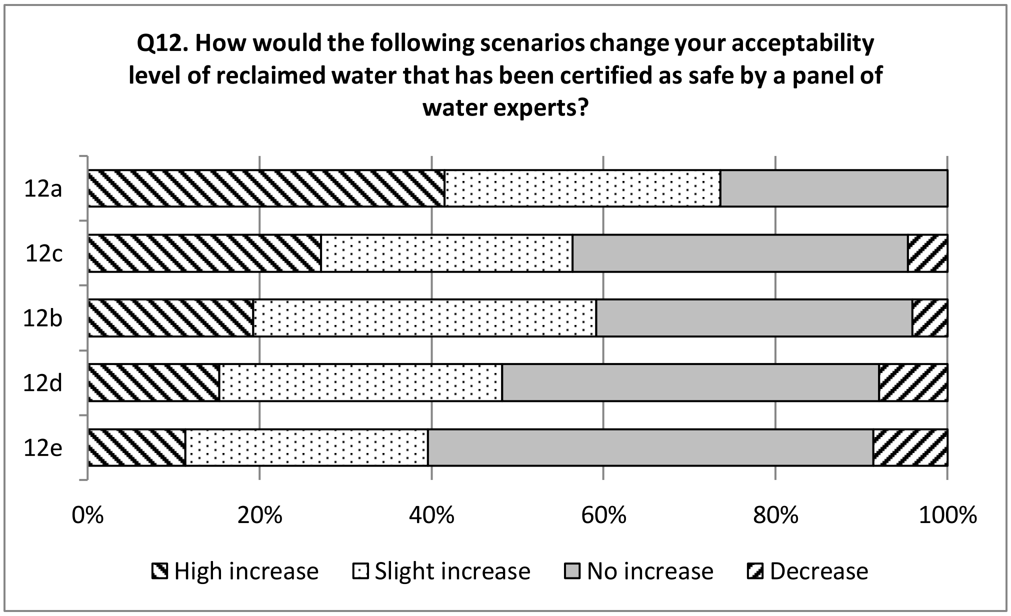


Figure 3-13: Question 12 - survey

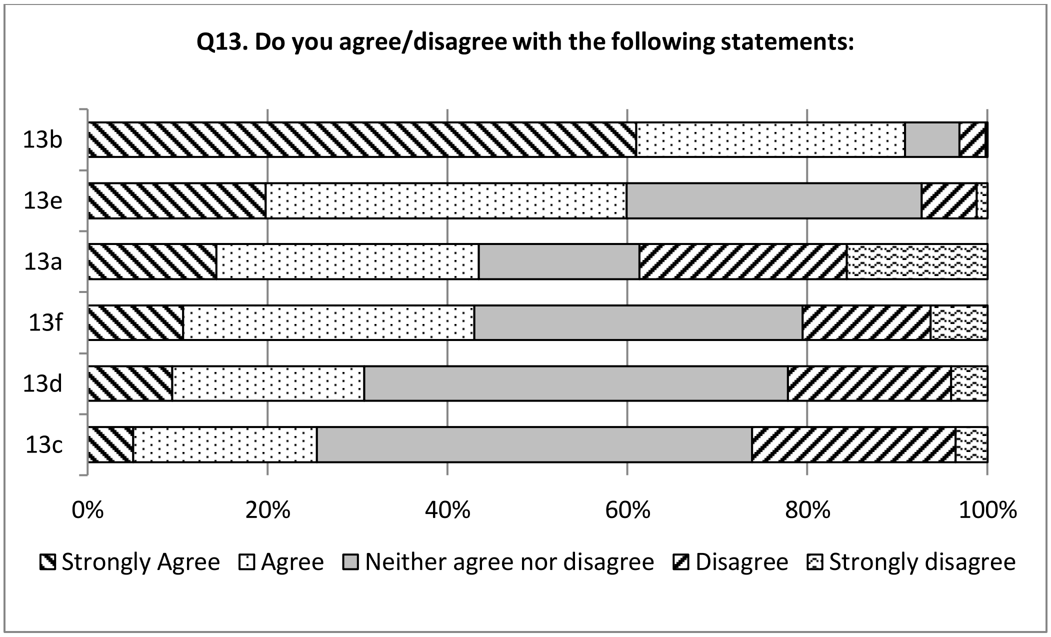


Figure 3-14: Question 13 - survey

Question 14 was an open ended question that gave the respondents the opportunity to comment on water reclamation. At total of 92 respondents submitted their comments regarding water reclamation initiatives. The following are a few of the respondents' comments randomly selected (simple random sample):

> Respondent # 18 : " I support use of water reclamation, but am absolutely puzzled that there is not an irrigation water system. I am baffled that we use potable water to water a lawn."
>
> Respondent # 22: "As long as water is treated for human consumption, I don't care where it comes from. So-called 'natural water' is not used without treatment (to remove run-off, sediments, fish feces, dead insects, or whatever) so I don't care about re-used/reclaimed water either. Unlike many of my contemporaries, I am not squeamish about these things and don't feel the need to live in an antiseptic, plastic bubble."
>
> Respondent # 40: "Water reclamation is a great idea. Most people don't understand a lot of times it's cleaner than the stuff coming out of their taps. It's a

psychological thing - we need a fairly significant paradigm shift before it will become publicly acceptable.”

Respondent # 60 : “I noted that reclaimed water wasn't acceptable for golf course or landscape irrigation because I think these are unnecessary. I don't think *any* water should be used for these.”

Respondent # 91: “Initiatives taken on campus regarding use of reclaimed water are a positive step forward. Continued education regarding the benefits and environmental savings of such programs need to be in the forefront of campus media (i.e. through the Facilities Management portion of the primary website)”

Respondent # 111: “I think water reclamation is very important and we need to study how this can be done safely. Global climate change (warming) is happening very quickly and water may become scarce much sooner than people think.”

Respondent # 121: It is difficult to know who to trust since the general public are uninformed about these processes and how the decisions are made and based on what?

Respondent # 137: I am concerned about lingering chemicals/pollutants in reclaimed water provided for drinking, cooking and bathing...

Respondent # 139: “I think that water renewability and abundance is an important topic that many North Americans do not often consider. Education of the general public on the situation of our extremely slowly renewing aquifers and the amount of usage our lakes and rivers are undergoing currently may improve support for water reclamation programs.”

Respondent # 175 : From a financial perspective, the ROI must make it feasible (at least break even). Would probably be easier to sell to the public if they didn't know the details - just say it's tested, safe, and the same as natural water.

Respondent # 177: Water is the most important resource on Earth, it should be treated as such. Using potable water to flush toilets is a waste of resources. Water

> from natural sources (lakes, rivers) should be protected from agricultural pollutants and screened very carefully before consumption. Water from aquifers should be protected since it would take a long time to renew. Water should be used wisely, having a golf course in places where water is scarce is not a wise use of it. Therefore I support the idea of water reclamation as a way to improve the efficiency of water use and to protect wet ecosystems

3.5 Discussion

Only 24% of the respondents correctly answered that the average daily domestic water usage by Canadians is approximately twice the global average. Therefore, it can be concluded that accurate knowledge of domestic water consumption among the university community is low. However, since only 9% of the respondents believe domestic water usage by Canadians is about the same as the world average, it can be deduced that the majority of the university community believes that water usage in Canada is excessive when compared to the rest of the world. This is especially true when other uses such as power generation and industry are taken into consideration. On the contrary, knowledge about fresh water availability in Canada is high, since 92% of the university community correctly answered this question. Although the majority of the university community (80.3%) knows that wastewater in London is treated by the municipal sewage treatment system, there is low to moderate knowledge of the urban water cycle in London, Ontario. Fifty percent (50%) of the university community knows where London's drinking water comes from and only 26.9 % knows where wastewater is released to, after treatment.

University faculty are more familiar with the terms "potable water" and "non-potable water" than students and staff. Furthermore, graduate student are more familiar with these terms than undergraduate students and university staff. Familiarity with the remaining terms specified in question 8, which are not significantly dependent on the occupation of the respondents, was higher for the terms "wastewater" (80.5%) "stormwater" (78.5%) and "recycle water" (68.1%).

Subsequently, the 6 questions of part 2 of the survey were recoded, computed and collapsed into a single ordinal variable named "water knowledge" with three symmetric categories: Low (1), moderate (2) and high (3) knowledge. It can be concluded that 60.4% of the university community has a medium level knowledge of water resources and urban water cycle in London, ON. Moreover, 13.8 % and 25.8 % of the university community has low and high water knowledge respectively. Table 3-9 shows the percentage of respondents from the university community that falls in each category. Figure 3-15 shows a histogram of these results.

KNOWLEDGE	**Percent**	**Cumulative Percent**
Low	**13.8**	13.8
Moderate	**60.4**	74.2
High	**25.8**	100.0

Table 3-9. Water knowledge

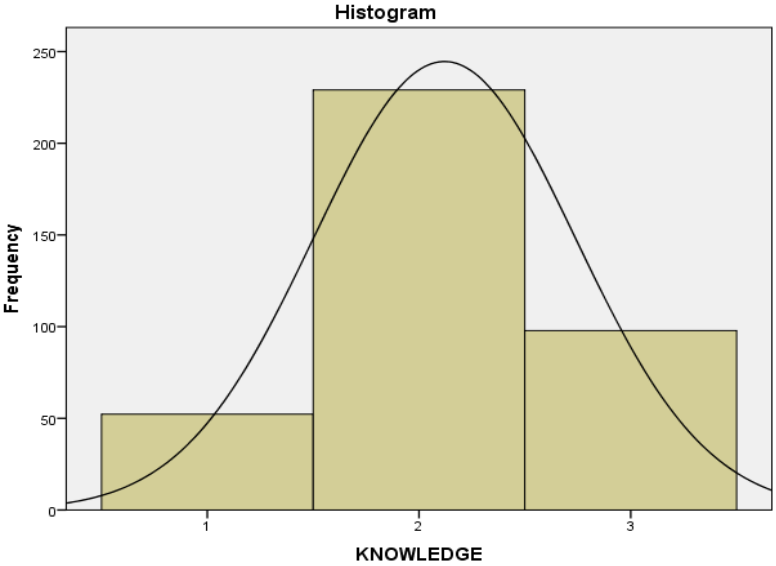


Figure 3-15. Histogram of water knowledge

Results of question 10 of the survey were consistent with previous studies regarding perceptions and acceptance of wastewater reclamation. Acceptability of reclaimed wastewater for application not involving drinking or close personal contact was very high (>85%) in all the stated cases, regardless of water availability. Acceptability of applications involving drinking or close personal contact showed higher variability depending on the respondent's perceived risk. These include: Drinking (42.1%), Cooking (51.1%), Public Swimming pools (63.6%), Bathing (67.2%), Food crops irrigation (72.9%), Vegetables irrigation (73.5%), Aquifer recharge (81.8%), Laundry (81.9%) and snow making (82.8%). However, when extreme drought conditions are considered, acceptability of applications involving drinking or close personal contact substantially increase. For instance, acceptability for Drinking increases from 42.1 % to 76.4 % and for Cooking from 51.1 % to 79.8 %.

Subsequently, the applications involving drinking or close personal contact of question 10 were recoded, computed and collapsed into a single ordinal variable named "close contact acceptability" with three symmetric categories: Low (1), moderate (2) and high (3) acceptability. The results show that 68.6% of the university community has a high acceptability of wastewater reclamation for applications involving drinking or close personal contact. Furthermore, 23.2 % and 8.1 % of the university community has medium and low acceptability. Table 3-10 shows the percentage of respondents from the university community that falls in each category. Figure 3-16 shows a histogram of these results.

ACCEPTABILITY (Drinking or close contact)	**Percent**	**Cumulative Percent**
Low	8.1	13.8
Moderate	23.2	31.4
High	68.6	100.0

Table 3-10: Close contact acceptability.

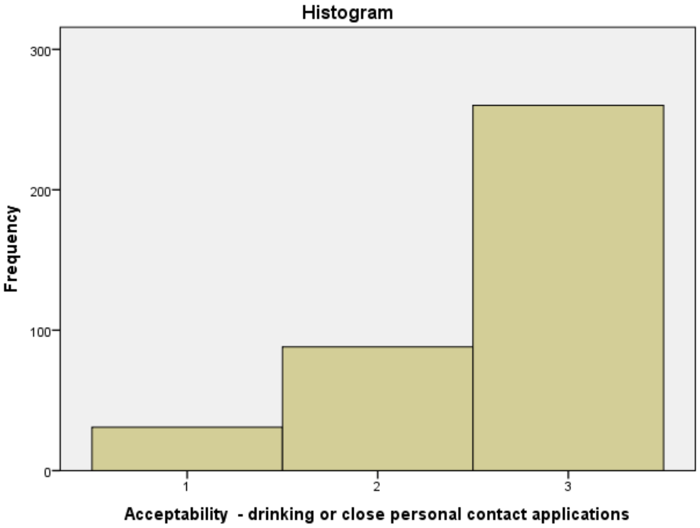


Figure 3-16: Histogram of close contact acceptability.

The strength and direction of the relationship between these two collapsed ordinal variables (knowledge and acceptability) was measured by the Goodman and Kruskal's Gamma method. Table 3-11 shows the cross tabulation results between the variables "water knowledge" and "close contact acceptability. The results from the Gamma test reject the Null Hypothesis ($p<0.05$) and shows that there is a moderate (0.303) positive relationship between "water knowledge" and "close contact acceptability" (see Table 3-12).

		Water knowledge			
CROSS TABULATION		**Low**	**Moderate**	**High**	**Total**
	Low	15.4%	6.6%	7.2%	7.9%
Close contact acceptability	**Moderate**	28.8%	26.6%	12.4%	23.3%
	High	55.8%	66.8%	80.4%	68.8%
		100.0%	100.0%	100.0%	100.0%

Table 3-11 Cross tabulation results between the variables "water knowledge" and "close contact acceptability"

Symmetric Measures

	Value	Exact Sig.
Gamma	.303	.001

Table 3-12. Gamma test results between the variables "water knowledge" and "close contact acceptability"

Responses to question 11 show that the university community has a high degree of trust in qualified university professors and the regional health unit when it comes to information on the safety of reclaimed water. Moderate level of trust was observed on the federal, provincial and local government, as well as, on private consultants and staff at the water treatment facility. Low degree of trust was observed regarding the media and the internet. High trust in the regional health unit may be due to its focus on public health issues. High trust in university professors may be due to the perception that research universities are more likely to consider issues and uncertainties, such as the effects of low term exposure to low concentrations of PPCPs, its degradation by-products and metabolites, without political interference.

Responses to question 12 show that acceptability increases substantially when the source of reclaimed water is perceived as cleaner than municipal wastewater, such as stormwater and greywater. The highest increase of acceptability was observed for stromwater (41.5 %), followed by a combination of stormwater and greywater (19.3%). Additionally, acceptability of reclaimed wastewater increased when it is put back into natural systems before use. The highest increase of acceptability was observed when treated wastewater is allows to percolate into an aquifer (27%), followed by lake augmentation (15.3%) and discharge into a river (11.4%).

Responses to question 13 show high agreement by the university community regarding two of the statements. First, 90.9 % of the university community agree that they would support water reclamation initiatives if the benefits to the environment are extensive and it is safe for humans. If we compare this to question 9 in which only 75.8 % of respondents considered water reclamation initiatives to be a good idea, we can infer that support increases if the safety to humans and benefits to the environment are clearly known. Second, 60 % of the university agrees that there is much scientific/technological uncertainty regarding the removal of chemicals such as pharmaceuticals from reclaimed water and the long-term effects on human health from exposure to these contaminants are not known. This highlights the importance of this type of research at post-secondary institutions.

3.6 Conclusions

The university community at Western University, London, Ontario, Canada are more likely to accept reclaimed wastewater for applications that do not involve drinking or close personal contact. However, acceptability for applications involving drinking or close personal contact improves when benefits to the environment are extensive, it is safe for humans, the source of reclaimed water is perceived as cleaner than municipal wastewater, and the reclaimed wastewater is put back into natural systems with long retention times such as aquifers. Western University professors and the regional health unit are considered the most trustworthy sources of information regarding the safety of reclaimed water by the university community. Knowledge of the urban water cycle and water resources in Canada is moderate among the university community and the Gamma measure of association shows that there is a moderate (0.303) positive relationship between “water knowledge” and “close contact acceptability”. The majority of the university community (75.8 %) thinks that reclaiming water to provide an alternate source of water in southwestern Ontario is a good idea, but there are still concerns with the presence of chemicals such as pharmaceuticals from reclaimed water and the long-term effects on human health from exposure to these contaminants. Wastewater reclamation is becoming an important alternative for sustainable water resources management not only in regions experiencing water scarcity but also in places that do not have scarcity issues, such as southwestern

Ontario, as a way to become resilient to changing climatic conditions and long term sustainability of fresh water resources.

3.7 References

Asano T., Burton F., Leverenz H., Tsuchihashi R. and Tchobanoglous G. Water Reuse : Issues, Technologies and Applications. Metcalf & Eddy – AECOM. McGraw-Hill. 2007.

Brooymans H.(2011) Water in Canada: a resource in crisis. Vancouver, BC. Lone Pine.

Canada Mortgage and Housing Corporation (CMHC). Research Report: Water Reuse Standards and Verification Protocol. 2005. www.cmhc.ca (accessed in August 2013).

City of London. City Wastewater Treatment. 2014. http://www.london.ca/residents/Sewers-Flooding/Sewage-Treatment/Pages/Wastewater-Treatment.aspx (accessed August 2014)

City of London. 2014. Water Quality. http://www.london.ca/residents/Water/Water-System/Pages/Water-Quailty.aspx. (accessed June 2014).

DMTI Spatial Inc. Canada Water (CW), Regional Municipality Boundaries (RMN) and Municipal Boundaries (MUN) shape files. 2012 edition. Scholars GeoPortal . http://geo2.scholarsportal.info/ (accessed in July, 2014)

Environment Canada. Wise Water Use. https://www.ec.gc.ca/eau-water/default.asp?lang=En&n=F25C70EC-1 . Date Modified: 2013-07-23. (accessed June 2014)

Exall C., Marsalek J. And Schaefer K. Water Reuse in Canada: Opportunities and Challenges. National Water Research Institute, Environment Canada. In P. Hlavinek et al (eds), Integrated Urban Water Resources Management, 253 – 262. 2006 Canadian Crown. Printed in Netherlands.

Haddad B., Rozin P., Nemeroff C. and Slovic P. The psychology of water reclamation and reuse : Survey findings and research road map. Water Reuse Foundation, 2009.

Health Canada (HC). Canadian Guidelines for Domestic Reclaimed Water for Use in Toilet and Urinal Flushing. January 2010. ISBN: 978-1-100-15665-1. Cat. No.: H128-1/10-602E. http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/reclaimed_water-eaux_recyclees/index-eng.php (accessed August 10, 2014)

National Research Council (NRC) of the national academics. Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater. National Academy of Sciences. 2012. ISBN: 978-0-309-25749-7.

Jimenez Blanca and Asano Takashi. Water Reuse. An international survey of current practice, issues and needs. 2008. IWA publishing.

Po M., Kaercher J. and Nancarrow B. Literature review of factors influencing public perceptions of water reuse. CSIRO Land and Water. Technical Report 54/03, December 2003

Rygaard M., Binning P., Albrechtsen H. Increasing urban water self-sufficiency: New era, new challenges. Journal of Environmental Management 92 (2011) 185e194

SASI Group (University of Sheffield) and Mark Newman (University of Michigan). 2006. Domestic Water Use. http://www.worldmapper.org/posters/worldmapper_map324_ver5.pdf (accessed May 2014)

Statistic Canada. 2016. Population of census metropolitan areas. http://www.statcan.gc.ca/ (accessed August 2016)

United Nations Educational, Scientific and Cultural Organization (UNESCO). The United Nations World Water Development Report. Managing Water under Uncertainty and Risk. 2012. Paris, France.

The University of Western Ontario (UWO). Facts & Figures 2013. http://www.uwo.ca/about/whoweare/facts.html (accessed May 2014)

Upper Thames River Conservation Authority. Upper Thames River Assessment Report: Municipal Drinking Water System Summary - City of London Water Supply System. 2011. http://www.sourcewaterprotection.on.ca (accessed May 2014)

Vedachalam S. And Mancl K. Water Resources and Wastewater Reuse: Perceptions of Students at The Ohio State University Campus. Ohio Journal of Science 110(5): 104-113, 2010.

Wintgens T., Salehi F., Hochstrat R. and Melin T. Emerging contaminants and treatment options in water recycling for indirect potable use. Water Science & Technology—WST, 57.1, 2008.

Chapter 4

4. Soil aquifer treatment of secondary effluents and combined sewer overflows in the high permeability soils of southwestern Ontario

(Results published in the conference proceedings of the 2016 Canadian Society for Civil Engineering, 14th International Environmental Specialty Conference)

4.1 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 wastewater are important approaches to reducing the pressure on fresh water availability (NRC, 2012). Reclamation of wastewater effluents is the process of treating wastewater to high quality standards to make it suitable for potable (direct and indirect) or non-potable applications.

Indirect potable 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). Indirect potable reclamation can be used to mitigate the depletion of groundwater levels, to protect coastal aquifers from saltwater intrusion, and to store surface water for future use (Wintgens et al., 2008). Furthermore, public confidence in water reclamation projects seems to be higher when the reclaimed water is put back into natural systems prior to be reused (Haddad et al., 2009; Dillon et al., 2006).

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; Bdur et al., 2009). 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 is a low cost alternative for wastewater reclamation which does not require much energy and chemical usage, making it suitable for developed and developing countries (Sharma et al., 2008). SAT is defined as a three-component treatment process consistent of the infiltration zone, vadose (unsaturated) zone and aquifer storage (AWWA-RF, 2001). It 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; NCSWS, 2001). The redox conditions in the unsaturated zone seems to have the most important effect of biological mediated reactions (AWWA-RF, 2001). 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; Gungor and Unlu, 2005).

Centralized wastewater reuse in Canada is limited to agricultural irrigation, and golf course and urban landscape irrigation, and there are not national guidelines or regulations for indirect potable reuse (Exall et al., 2006). However, it is important to keep in mind that by discharging wastewater effluents directly or indirectly into drinking water sources, we are engaging in unintended indirect potable reuse by surface water augmentation. The lack of interest and legislated support for water reclamation in Canada may be driven by the general belief that Canada is a water rich country with a limitless supply of fresh water. Nonetheless, although Canada possesses 20% of the world's total freshwater resources, only 7 % is renewable.

Unlike Canada, the United States, Australia, Europe and many countries in the Middle East have developed national guidelines for wastewater reclamation (Jimenez et al., 2008). For instance, the US EPA developed guidelines for domestic wastewater reuse regarding water quality criteria and treatment requirement for different reuse applications (EPA, 2004). Additionally, several states have their own regulations and incentives (Jimenez et al., 2008). US EPA guidelines for potable groundwater aquifer recharge by SAT, recommends secondary treatment followed by disinfection. Additionally, reclaimed water should meet drinking water standards after percolation through vadose zone and require a setback distance of minimum 150 m to extraction wells, a vadose zone of at least 2 m deep and underground retention of at least 6 months prior to withdrawal (US-EPA, 2004). Acceptability of reclaimed wastewater has been shown to increased when it is put back into natural systems before use (Velasquez and Yanful, 2015). The purpose of this research was to investigate the prospect of SAT 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.

4.2 Study site

Southwestern Ontario in a secondary region in southern Ontario, with a population of approximately 3.5 million. Main sources of drinking in southwestern Ontario water include the Great Lakes (Lake Erie and Lake Huron) and groundwater. For instance, the City of London, which is the largest city in southwestern Ontario with a population of 366,151 (2011 census), relies on the Lake Huron and Lake Erie as drinking water sources. Additionally, a network of 7 groundwater wells is maintained as back up for emergency situations (City of London, 2014; UTRCA, 2011). Moreover, the Regional Municipality of Waterloo, also part of Southwestern Ontario, with a combined population of 507,100 (2011 census) mainly rely on buried, “semi-confined” aquifers for drinking water (Region of Waterloo, 2010). Although, southwestern Ontario is generally considered abundant in water resources, it is not immune to drought or serious water shortages. Ontario has experienced some of the driest conditions ever on record for the province over the past decades. For example, in 2001, the Great Lakes region experienced the driest summer in

54 years of record which caused significant crop losses in southwestern Ontario (ECO, 2007).

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 as shown in figure 4-1 (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). The Udden-Wentworth grain size classification scheme (Wentworth 1922) defines fine grain size between 0.125 to 0.25 mm and medium grain size between 0.25 and 0.50 mm. Figures 4-2 and 4-3 show high permeability soils of southwestern Ontario classified by primary material.

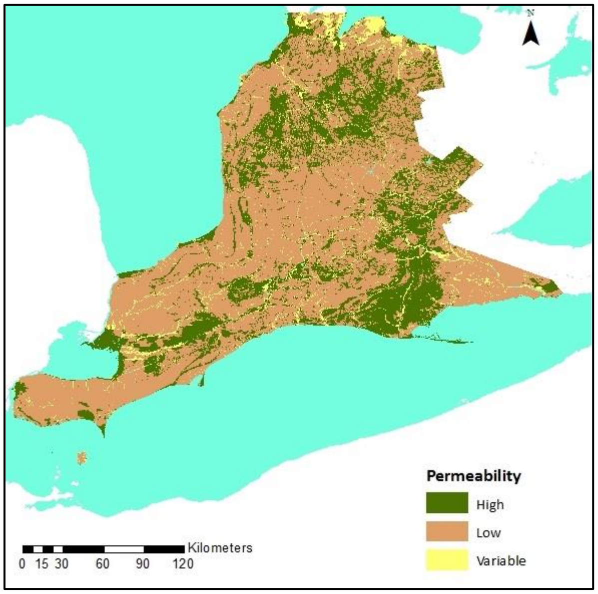
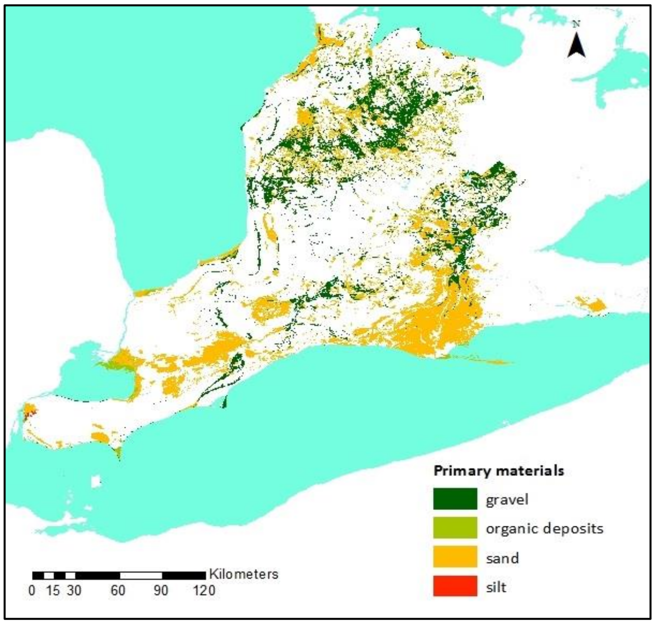
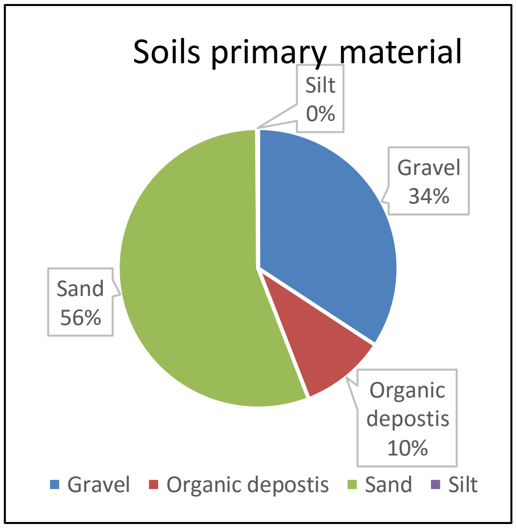


Figure 4-1: Surficial permeability southwestern Ontario

Source: OGS, 2010





Figures 4-2 and 4-3. Primary material composition of high permeability soils in southwestern Ontario

Source: OGS, 2010

Domestic wastewater in southwestern Ontario is generally of weak strength in terms of BOD_5 due to high potable water consumption. For instance, average influent and effluent BOD_5 at the Adelaide Pollution Control Plant (APCP) in London, Ontario, Canada in 2014 were 128 mg/L and 3 mg/L respectively (APCP, 2015). Effluent limits for monthly averages set by Ontario Ministry of the Environment Certificate of Approval No. 7397-96SPH7 for the APCP are 10 mg/L for $CBOD_5$ and Total Suspended Solids, 1 mg/L for Total Phosphorus, 0.1 mg/L for unionized ammonia and 200 CFU/100 ml (geometric mean) for *E.coli* during disinfection season (MOE, 2013). Furthermore, federal wastewater effluent discharge regulations specified under the Fisheries Act are less stringent: 25 mg/L for $CBOD_5$ and Total Suspended Solids, 1.25 for mg/L for unionized ammonia expressed as nitrogen and 0.02 mg/L for residual chlorine, if chlorine, or one of its compounds, are used in the treatment of wastewater (Government of Canada, 2012).

4.3 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. Dimensions of the column were selected based on previous laboratory scale SAT studies (Guizani et al., 2011; Abel et al., 2014; Essandoh et al., 2013; Ak and Gunduz, 2013). 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 4-4 shows a schematic representation of the experimental set up.

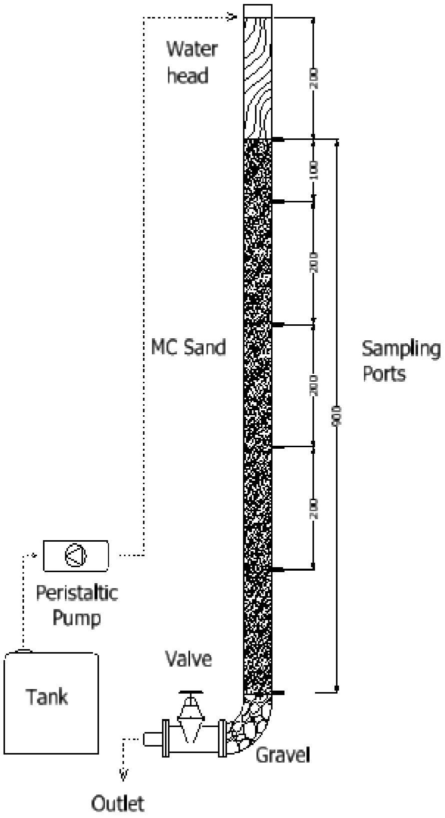


Figure 4-4: Schematic representation of the experimental set up

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 ^{o}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/cm^3. The bottom 20 cm of the column were filled with gravel to support the sand.

Grain size distribution graph of the sieved MC sand is shown in figure 4-5. Graphic geometric mean and standard deviation were measure as 1.9 Φ and 0.55 Φ (moderately well sorted) respectively. Specific gravity was measured using a Pycnometer (ASTM D 854-00) as 2.65. Additionally, major oxides composition (wt%) and trace elements (ppm) in the sieved MC sand were determined by Fusion X-Ray Fluorescence (XRF) and pressed pellet XRF respectively (tables 4-1 and 4-2). Average total organic carbon content was measured as 3 % (n=4) by TOC analyzer. Porosity and total pore volume were calculated as 42 % and 831.4 cm^3 respectively.

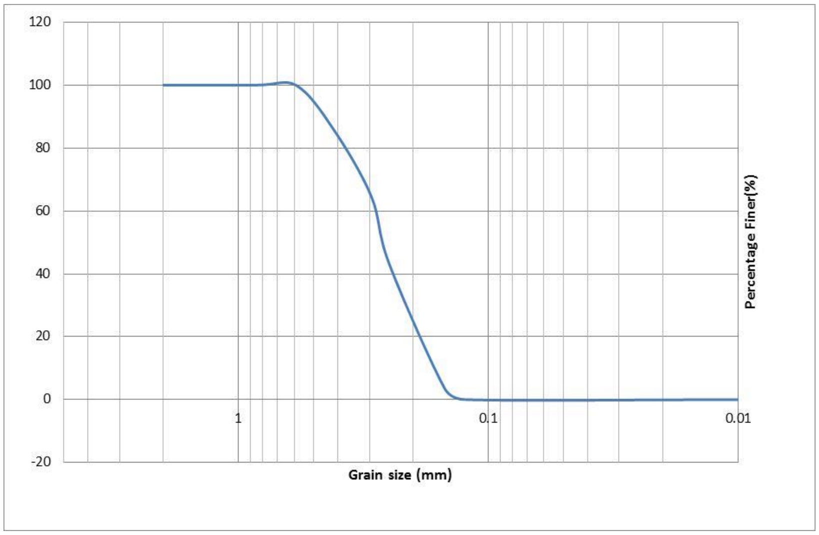


Figure 4-5: Particle size distribution – sieved MC sand

Major oxides MC sand			
	Wt%		Wt%
SiO_2	60.10	TiO_2	0.26
Al_2O_3	7.23	MnO	0.05
Fe_2O_3	1.80	P_2O_5	0.08
K_2O	1.45	Cr_2O_3	0.02
Na_2O	1.95	BaO	0.05
MgO	2.51	SrO	0.04
CaO	12.70	L.O.I.	11.70

Table 4-1: Major oxides composition of the sieved MC sand measured by Fusion XRF (wt%)

Trace elements MC Sand			
	ppm		ppm
Mo	2	Ga	7
Nb	5	Zn	26
Zr	87	Cu	12
Y	17	Ni	6
Sr	265	Co	3
U	3	Mn	348
Rb	66	Cr	61
Th	6	V	23
Pb	< 5	Ba	365
As	9	Sc	< 5

Table 4-2. Trace elements in the sieved MC sand measured by pressed pellet XRF (ppm)

The laboratory scale SAT system was operated with wastewater for a period of 10 consecutive months (May 2014 – February 2015) on cycles of 7 days wetting and 7 days drying at 20 ^{0}C (± 1^{0}C). This operational schedule is typical of SAT systems and provides sufficient drying time to restore surface permeability and increase the column redox potential (Bouwer, 2002; Harun, 2007; He et al., 2016). The drying cycle was performed at a room temperature of 20 ^{0}C (± 1^{0}C), where air was allowed to naturally diffuse into the soil column for 7 days. However, moisture retention by the soil was expected since the volumetric soil moisture content remaining at field capacity is about 15 to 25% for sandy soils (NRCCA, 2010). 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 12 months of operation is presented in Table 4-3. Collected wastewater was fed to the top feeding tank by the peristaltic pump at an appropriate flow rate to maintain the specified constant head while minimizing weir overflow. Flexible tubing and storage tanks were sterilized every drying cycle with sodium hypochlorite (8.25 %) to remove any biofilm formed during the operation.

Experiments	Column influent	HRT (hours)	Hydraulic conductivity K (m/d)
A	Secondary Effluent	1.4	5.5
B	Secondary Effluent	2.8	2.7
C	Secondary Effluent	13.9	0.5
D	Combined Sewer Overflows	2.8	2.7
E	Secondary + methanol (1:1)*	2.8	2.7
F	Secondary + methanol (1:3)*	2.8	2.7
G	Secondary + methanol (1:6)*	2.8	2.7
E	Secondary + glucose (1:1)*	2.8	2.7
F	Secondary + glucose (1:3)*	2.8	2.7
G	Secondary + glucose (1:6)*	2.8	2.7

*Nitrogen to carbon Ratio

Table 4-3: Summary of experiments

Secondary effluent and raw wastewater were both collected from the Adelaide Pollution Control Plant (APCP) in London, Ontario, Canada and stored at 4 ^{o}C in 5 gallons high density polyethylene drums. Since the column was operated at 20 ^{0}C (± 1^{0}C), stored wastewater was allowed to acclimatize to the column operating conditions before introducing it into the system. The APCP provides secondary level treatment to industrial and domestic 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_5 removal and nitrification. Phosphorous removal is achieved by the addition of cationic polymers and iron salts and disinfection, between April 1 and September 30, by ultraviolet light (City of London, 2014). Average raw and final effluent characteristics APCP in 2014 are shown in Table 4-4. Furthermore, Total chemical oxygen demand (TCOD) and soluble chemical oxygen demand (SCOD) concentrations in the raw influent are 314 ± 36 mg/L and 124 ± 44 mg/L respectively (Gandhi et al., 2013).

Average secondary effluent characteristics at APCP in 2014

		Average	**Min**	**Max**
Temp	^{o}C	16.8	10.8	22.4
BOD - Raw	mg/L	128	44.2	598
BOD - Final	mg/L	3	1	8
Suspended Solids - Raw	mg/L	153	31	1540
Suspended Solids - Final	mg/L	3	1.5	10
Total Phosphorus - Raw	mg/L	4.2	1.96	21.1
Total Phosphorus - Final	mg/L	0.58	0.28	1.31
Total Ammonium - N - Raw	mg/L	18.1	26.3	7.1
Total Ammonium - N - Final	mg/L	0.4	0.1	3.7
TKN - Raw	mg/L	29.1	20.9	39.6
TKN - Final	mg/L	2	0.4	5.4
NH_3 - N - Final	mg/L	0.003	0	0.032
NO_3^- - N - Final	mg/L	16.4	7.5	21.6
*E.coli** - Final	CFU/100 ml	8 (G.M.)	6	11
DO - Final	mg/L	7.4	9	5

**E.coli* is only measured from April to September

Table 4-4. Average secondary effluent characteristics at APCP in 2014

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), *E. coli*, total coliforms, ammonia (NH_3), phosphate ions (PO_4^{3-}), Nitrate ions (NO_3^-) and Sulphate ions (SO_4^{2-}) at all column depths. Simulated CSOs used for experiment D were analyzed for Dissolved oxygen (DO), Biological Oxygen Demand (BOD_5), Total Nitrogen (TN), total coliforms and *E.coli* at all column depths. Experiments

E, F, G, H, I and J were analyzed for dissolved nitrate ions (NO_3^-) at all column depths. Dissolved oxygen was also measured at the column inflow and effective length of 90 cm every 24 hours for Experiments A, B, C and D. Flow rate was measured daily to monitor column clogging. 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.

4.3.1 Analytical Techniques for Water Constituents

Dissolved Nitrate (NO_3^-), sulphate (SO_4^{2-}) and phosphate (PO_4^{3-}) ions were measured using High Performance Liquid Chromatography (HPLC) with a Conductivity Detector (detection limits of 50, 75 and 125 µg/L respectively). Ammonia nitrogen and total nitrogen were measured by the salicylate method (detention limit: 0.4 mg/L) and persulfate digestion method (detention limit: 2 mg/L N) respectively. Total coliforms and *E. coli* were measured by Membrane Filtration Method (Sensitivity: 1 CFU/100 mL). DOC was measured using a SHIMADZU TOC analyzer for solids and liquids (range: 4µg/L to 4,000mg/L). Dissolved Oxygen was measured at the time of sampling using a portable digital meter (range: 0.1 - 20 mg/L) and BOD_5 was measured following the standard method for the examination of water and wastewater (Method 10230).

Percentage removal efficiency by the soil column were calculated with the following formula:

$$Removal_{\,i}(\%) = \left(1 - \frac{Eff\ Conc_{\,i}}{Inf\ Conc}\right) \times 100$$

Where *Removal* $_i$ is the percentage removal efficiency at sampling port i, *Inf Conc* is the concentration at 0 cm sampling port, and *Eff Conc* $_i$ is the effluent concentration at sampling port i. Sampling ports were placed at 0, 10, 30, 50, 70 and 90 cm depth. Majority of concentrations were measured as mg/L except *E.coli* and *total coliforms*, which were measured as colony forming units by 100 ml of sample (CFU/100).

Reaction rates were calculated using the mass balance equation assuming steady state conditions for each of the section of the column between sampling ports.

Accumulation rate = Input rate – Output rate ± Reaction rate

$$\frac{d(VC)}{dt} = QiCi - QoCo - VR$$

4.4. Results and Discussion

4.4.1 Soil aquifer treatment of secondary effluents (Experiments a, b and c).

During experiments A, B and C the SAT system was operated with secondary effluents collected from the APCP for and were run at simulated hydraulic conductivities of 0.5, 2.7 and 5.3 m/d respectively, which are representative of fine to medium grained sands (Bower, 1987). 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.

4.4.1.1 Dissolved Oxygen

Dissolved oxygen in the secondary effluents was measured 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. Each of the experiments A, B and D was run for 3 wetting/drying cycles which allowed for three sets of data collection at each of the hydraulic retention times. Average inflow (0 cm port) DO was measured as 8.04 mg/L (SD= 0.42). Results for average daily percentage DO consumption are shown in figures 4-6 to 4-8.

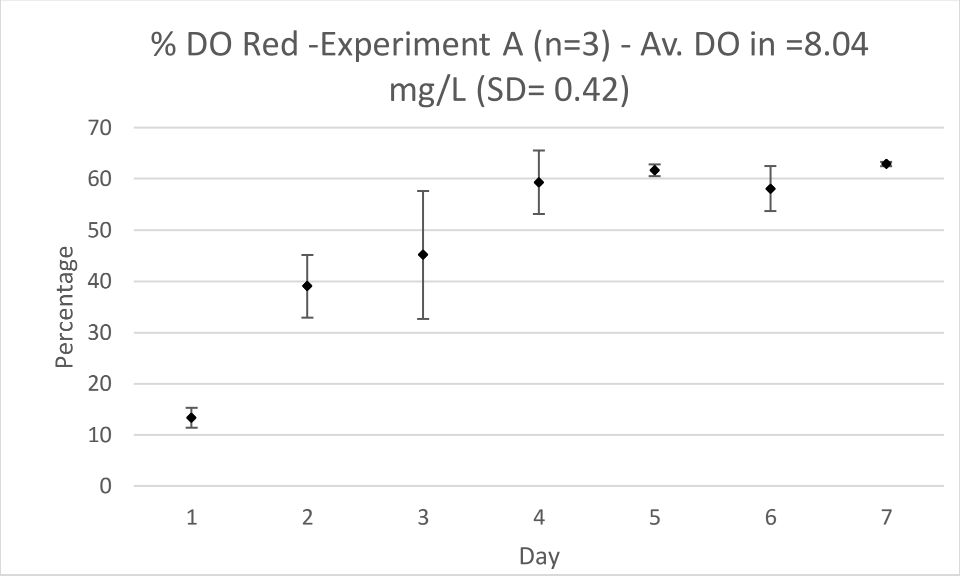


Figure 4-6: Average daily DO consumption (%) – 7 days wetting cycle – experiment A

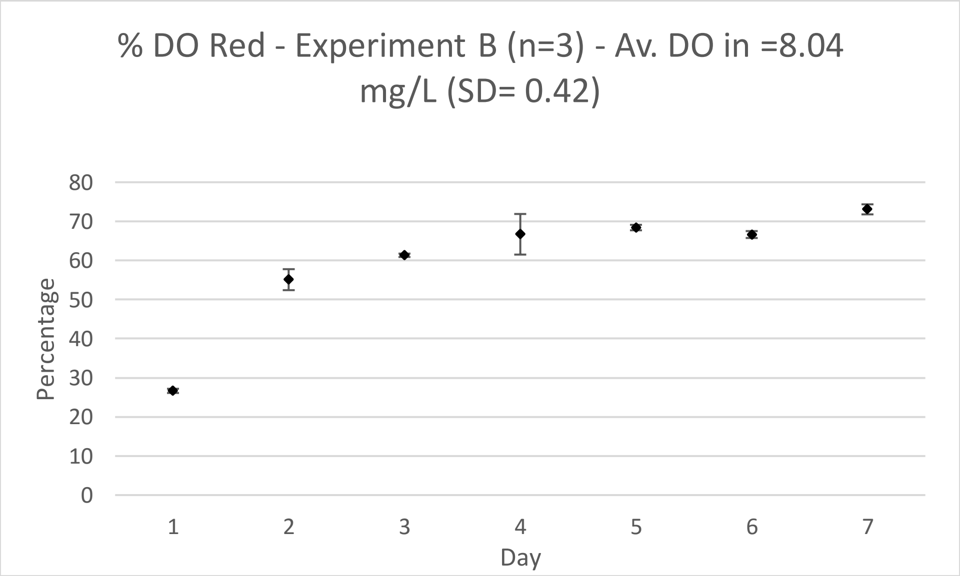


Figure 4-7: Average daily DO consumption (%) – 7 days wetting cycle – experiment B

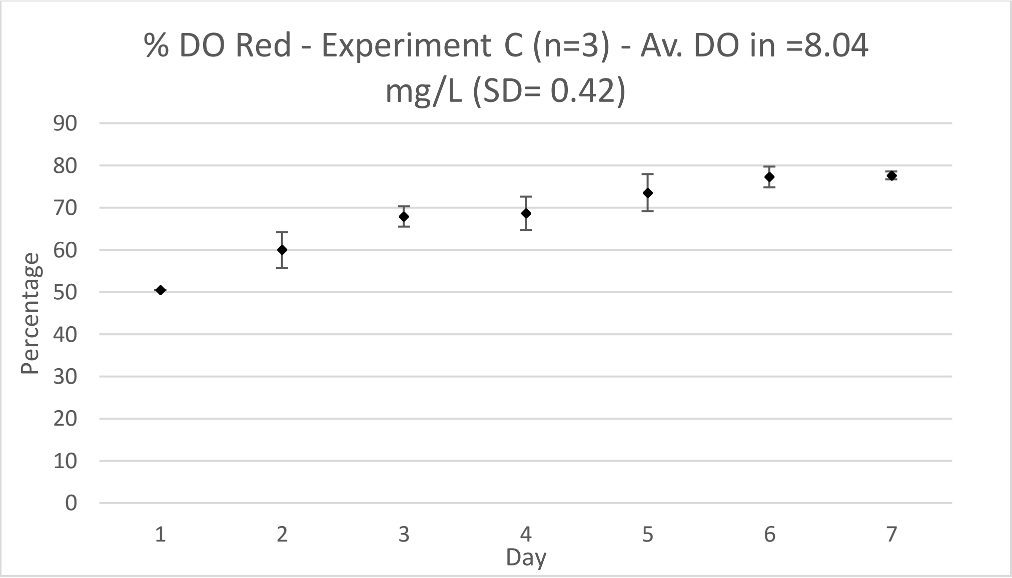


Figure 4-8: Average daily DO consumption (%) – 7 days wetting cycle – experiment C

Additionally, samples taken from all the ports (0, 10, 30, 50, 70, 90 cm) on the 7 day of wetting were analyzed for dissolved oxygen. Average inflow DO was measured as 7.52 mg/L (SD= 1.59). Average residual DO at the 90 cm depth was 2.94 mg/L, 1.6 mg/L and 1.99 mg/L for experiments A, B and C respectively. Moreover, average percentage DO consumption at the 90 cm depth was 62.69 %, 72.32 %, 77.64 % for experiments A, B and C respectively. Results for average percentage DO consumption are shown in figures 4-9 to 4-11.

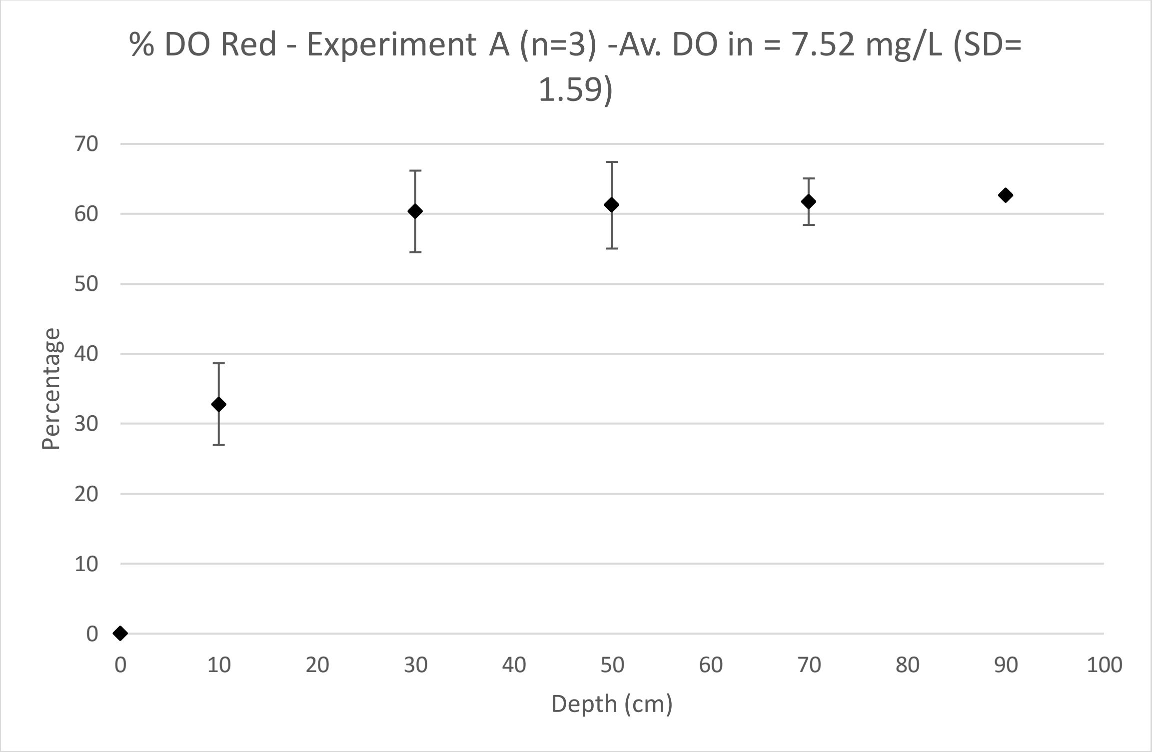


Figure 4-9: Percentage DO reduction by column depth – experiment A

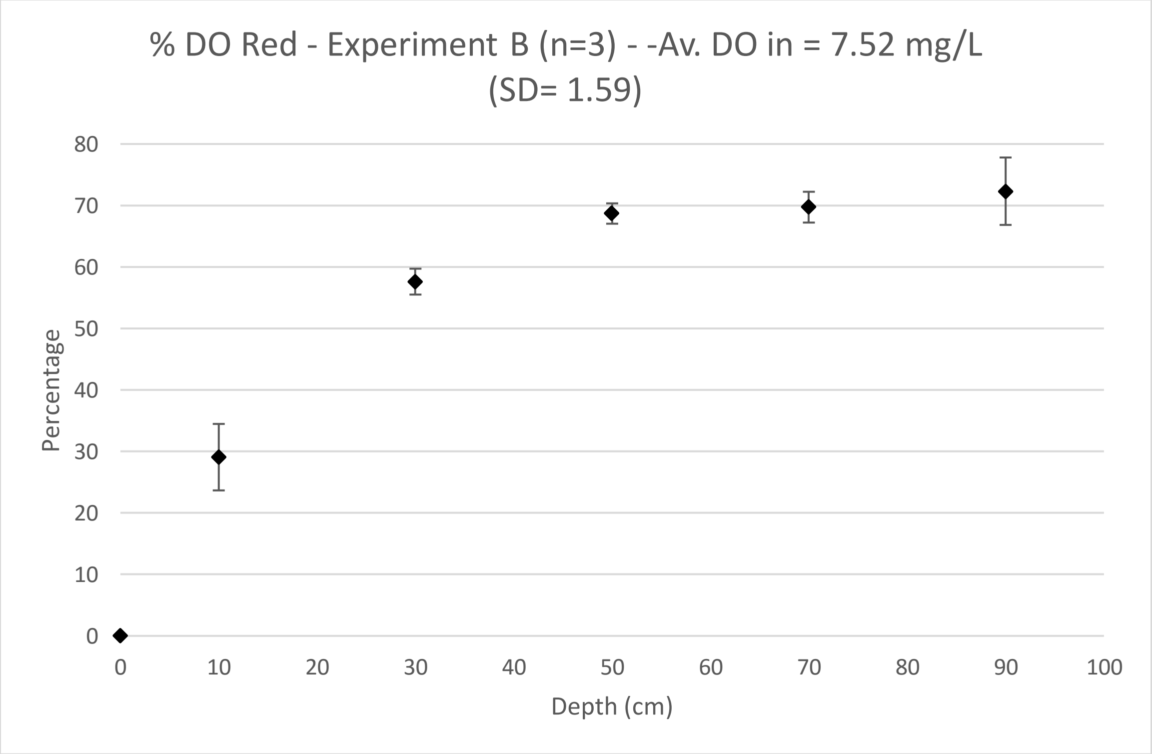


Figure 4-10: Percentage DO reduction by column depth – experiment B

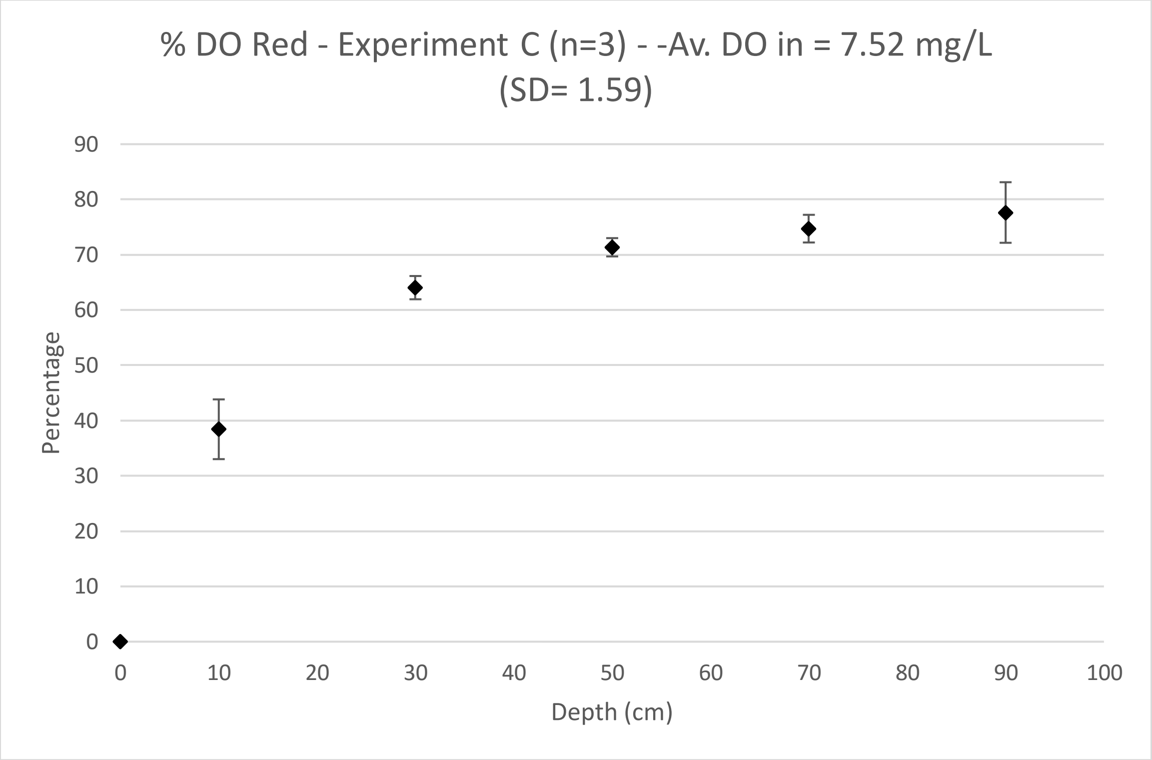


Figure 4-11: Percentage DO reduction by column depth – experiment C

Results show that oxygen consumption during the wetting cycle is proportional to the hydraulic retention time for experiments with secondary effluent. See figure 4-12. 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. Average DO consumption rates from the secondary effluents normalized by hydraulic retention time are shown in figure 4-12. Total DO consumed by the column in one HRT for experiments A, B and C is 3.96 mg/L, 4.57 mg/L and 4.87 mg/L respectively. It is also observed in experiments A, B, and C 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. Oxygen for organic matter biodegradation is provided by the secondary effluents and also by air in the pore spaces in the soil. 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; Cha et al., 2005; Harun, 2007). The column outflow was measured on a daily basis. There was no clogging of the column during these experiments conducted with secondary effluent.

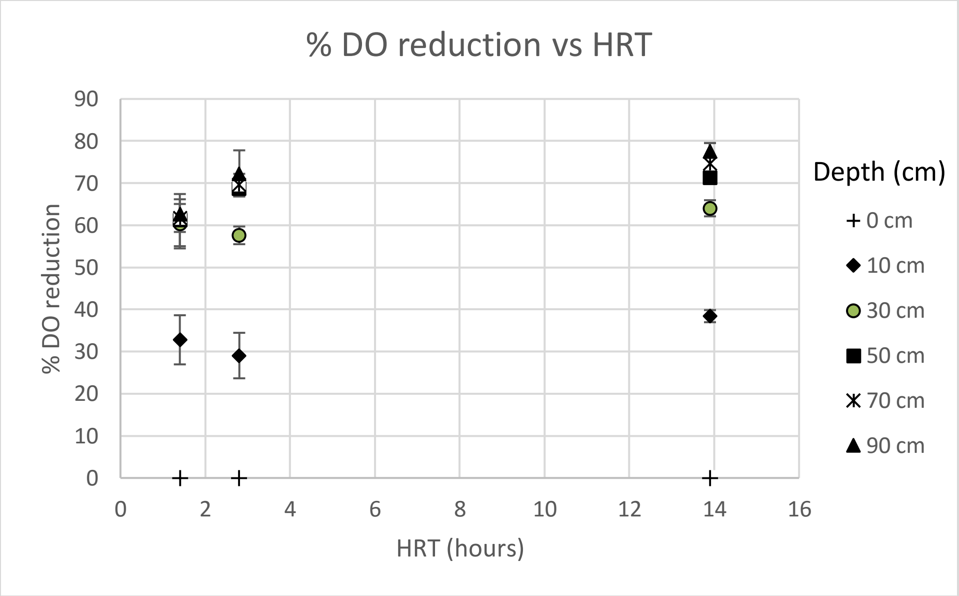


Figure 4-12. % DO reduction vs HRT by depth

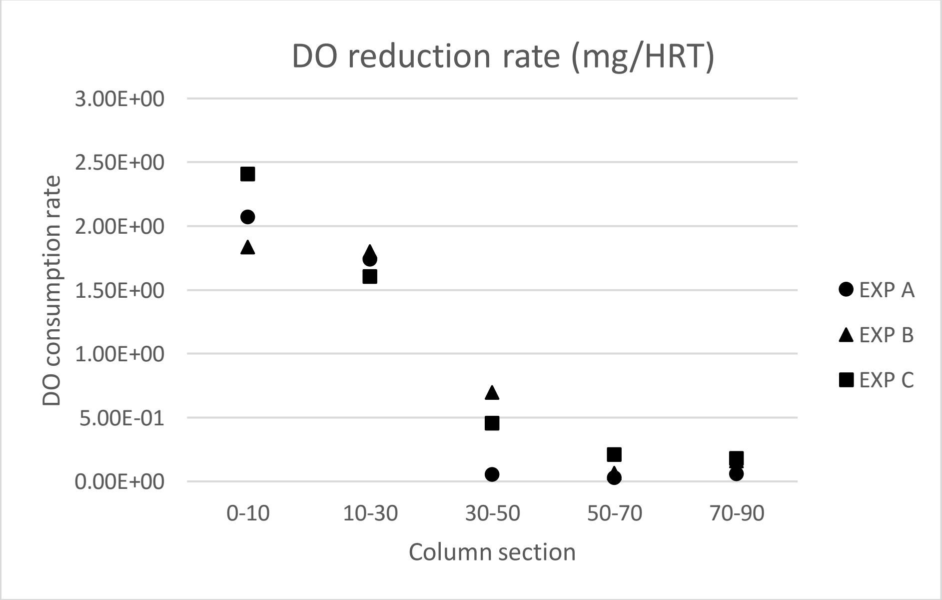


Figure 4-13. DO consumption rate (mg/ HRT)

4.4.1.2. Dissolved Organic Carbon

Dissolved Organic carbon (DOC) was measured at all the sampling depths for experiments A, B and C. Organic matter in secondary effluents from biological treatment is mainly composed of non-readily biodegradable carbon, natural organic matter, 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). Aerobic biodegradation stoichiometry of domestic wastewater is shown below. Theoretically, 1.067 grams of oxygen are needed for every gram of carbon oxidized to $C0_2$. However, DOC in secondary effluents is present is less biodegradable or non-biodegradable forms.

$$1/50\ C_{10}H_9O_3N + \frac{1}{4}\ O_2 = 9/50\ CO_2 + 1/50\ NH_4^+ + 1/50\ HCO_3^- + 7/50\ H_2O$$

Average DOC and BOD_5 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. Results are shown in figures 4-14 to 4-16.

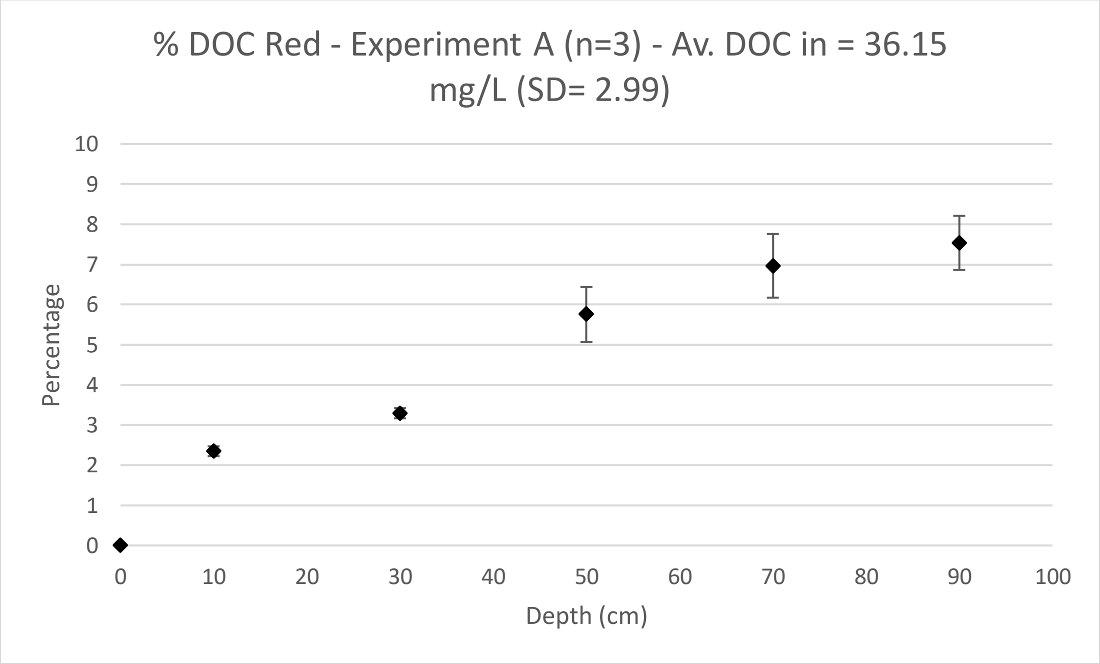


Figure 4-14: Percentage DOC reduction by column depth experiment A

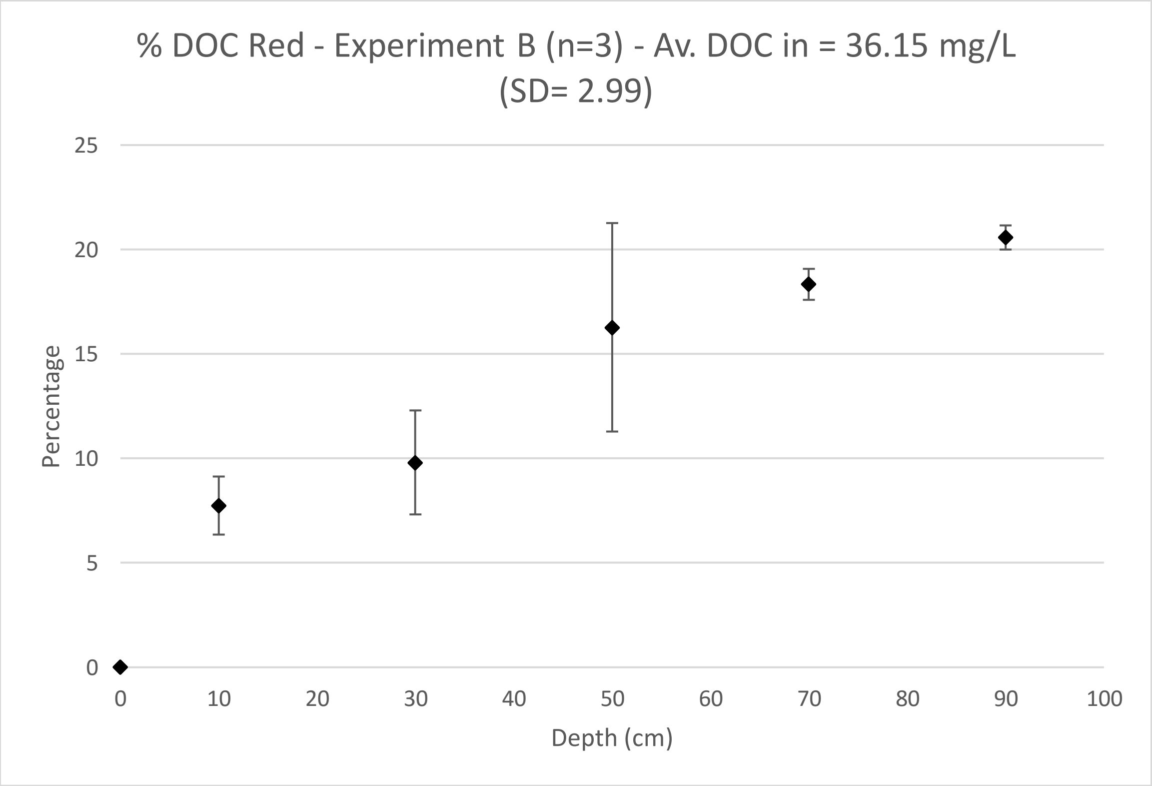


Figure 4-15: Percentage DOC reduction by column depth experiment B

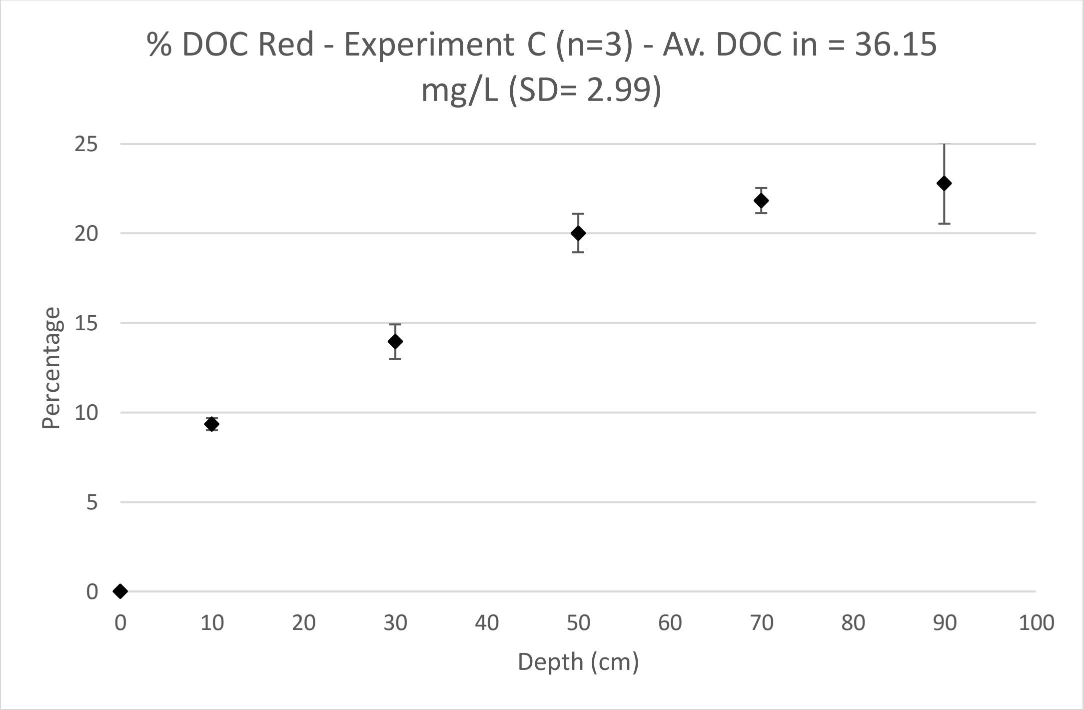


Figure 4-16: Percentage DOC reduction by column depth experiment C

Removal of DOC from secondary effluents showed dependency on both retention time and column depth up to approximately 50 cm. Relationships between percentage DOC reduction and hydraulic retention time (HRT) by column depth are shown in figure 4-17. A maximum DOC removal of 22.81 % from secondary effluents was achieved in experiment C, which had the longest retention time. 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; Cha et al., 2004). The Ontario Drinking Water Standards, Objectives and Guidelines (2003) suggest maximum DOC concentration of 5 mg/L as an Aesthetic Objective.

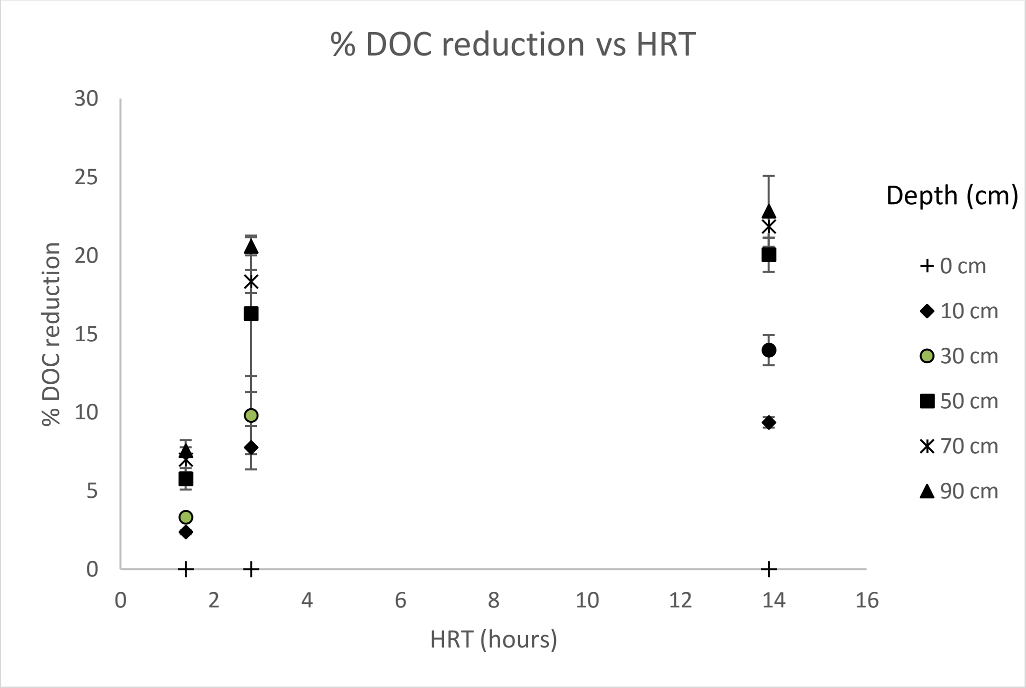


Figure 4-17: Percentage DOC reduction VS HRT by column depth

Positive correlations are observed between % DO consumption and % DOC reduction for the first section of the curves (S1). These first section of the curves suggests DOC removal mainly due to aerobic biodegradation with some adsorption. The second section of the curves (S2) where DOC reduction increases but DO does not decrease significantly suggests removal due to adsorption as predominant. This is consistent with the DO reduction results that show higher biologically activity in the first 30 to 50 cm of the column. See figure 4-18. Average DOC consumption rates normalized by hydraulic retention time are shown in figure 4-19. Total DOC consumed by the column in one HRT for experiments A, B and C is 2.29 mg/L, 6.25 mg/L and 6.88 mg/L respectively.

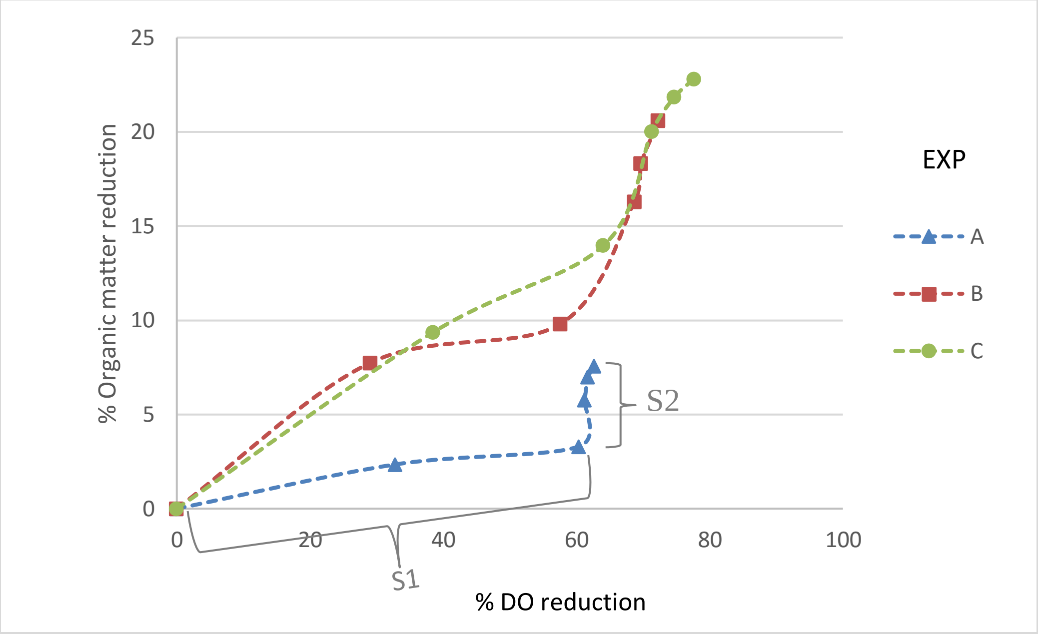


Figure 4-18: Average % DOC reduction vs average % DO consumption

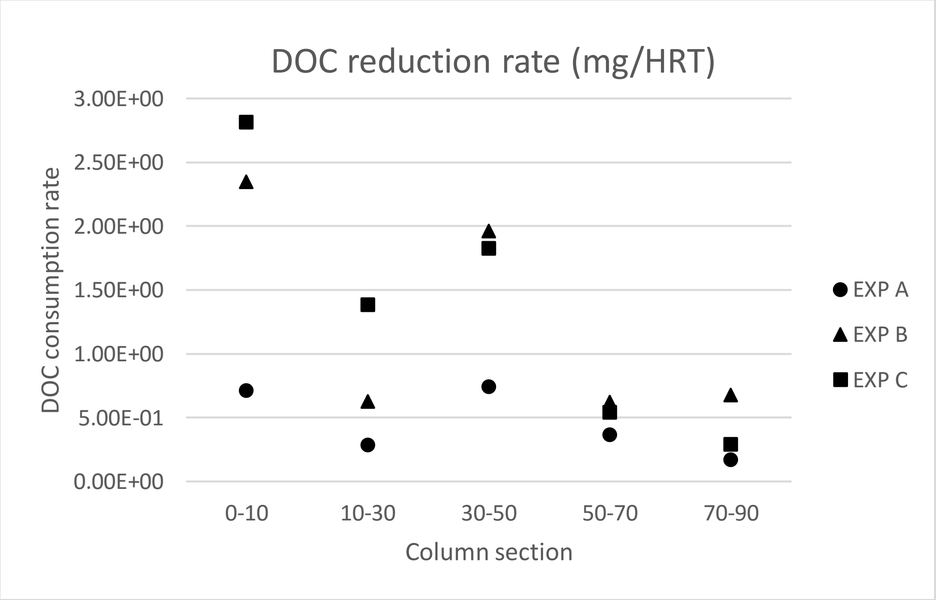


Figure 4-19: DOC consumption rate (mg/ HRT)

Mechanisms of organic carbon removal in SAT is a combination of biodegradation and adsorption. However, the sustainability of SAT systems depends on biodegradation (Fox et al., 2005). Biodegradation occurs under different electron acceptors depending on the redox conditions (aerobic, anaerobic or anoxic). Dissolved Organic matter reduction shows that the SAT column operates under aerobic conditions at the three retention times, where DO is the main elector acceptor. Dissolve organic matter in biologically treated secondary effluents is mainly composed of cell fragments and macromolecules (Shon et al., 2007).

4.4.1.3 *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 inflow secondary effluent was measured as 179 CFU/100 ml. Additionally, Geometric mean total Coliform concentrations in the secondary effluent was measured as 1416 CFU/100 ml. *E.coli* was not detected 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. Therefore, it can be concluded that at least a log 3 removal is achieved at the 90 cm depth. Likewise, total coliforms were almost completed removed at the 90 cm depth at experiments A (> log 3), B (log 1.7) and C (log 2.1). Log reductions of *E.coli* concentrations are shown in figures 4-20 to 4-22. Log reductions of total coliforms concentration are shown in figures 4-23 to 4-25.

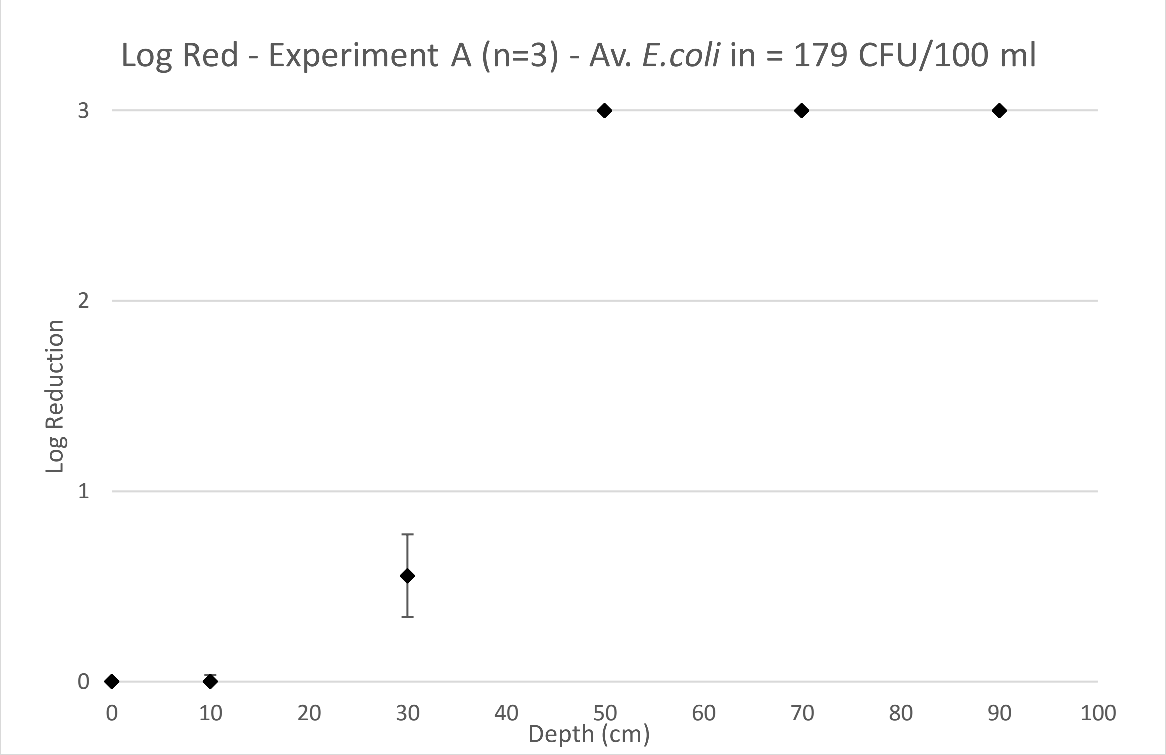


Figure 4-20. Log reduction of *E.coli* by column depth – experiment A

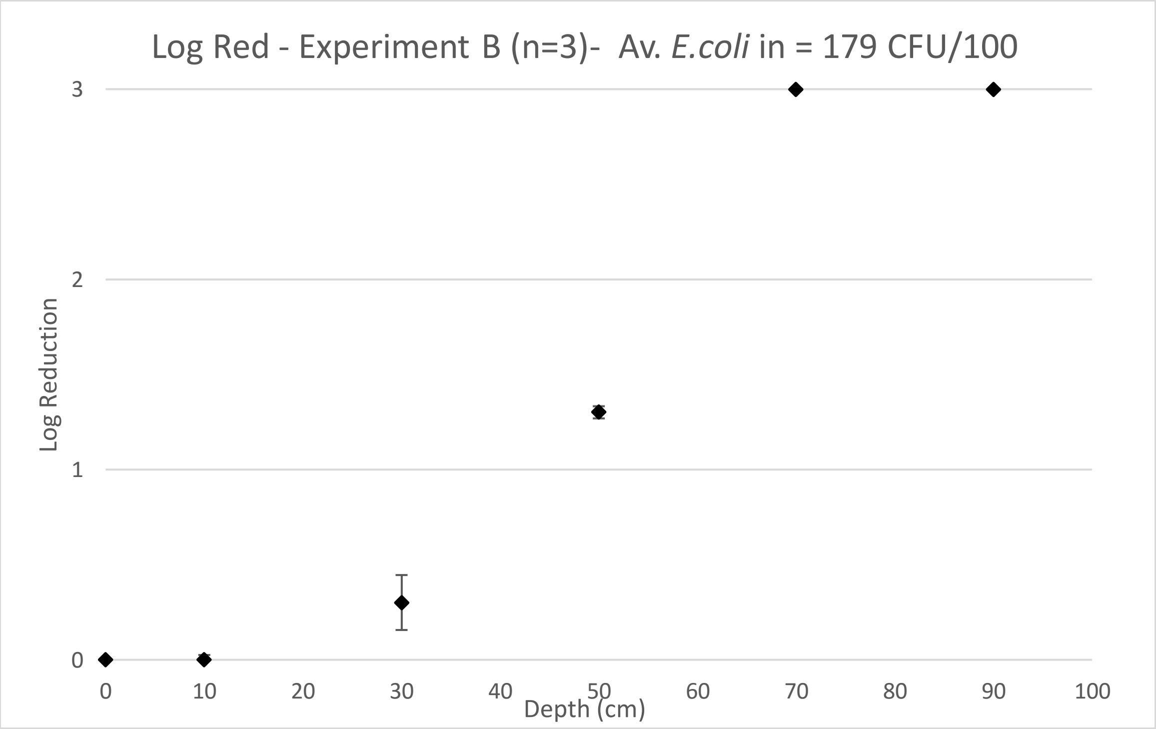


Figure 4-21. Log reduction of *E.coli* by column depth – experiment B

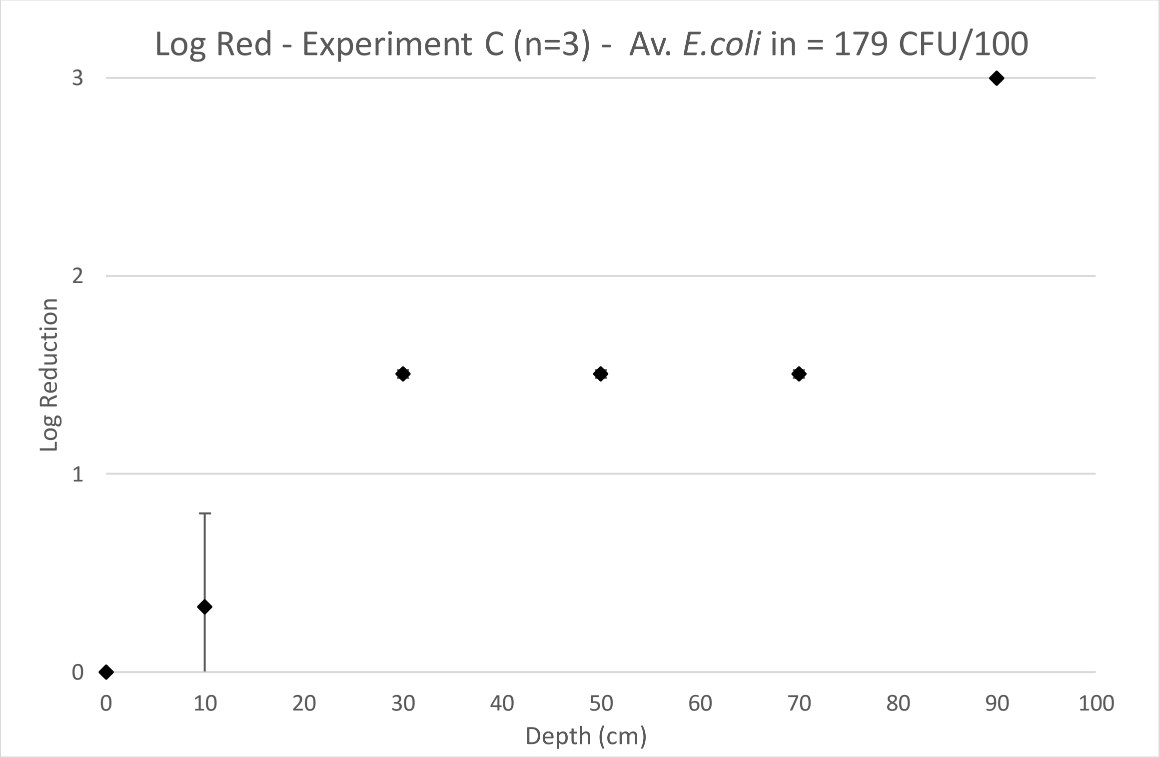


Figure 4-22. Log reduction of *E.coli* by column depth – experiment C

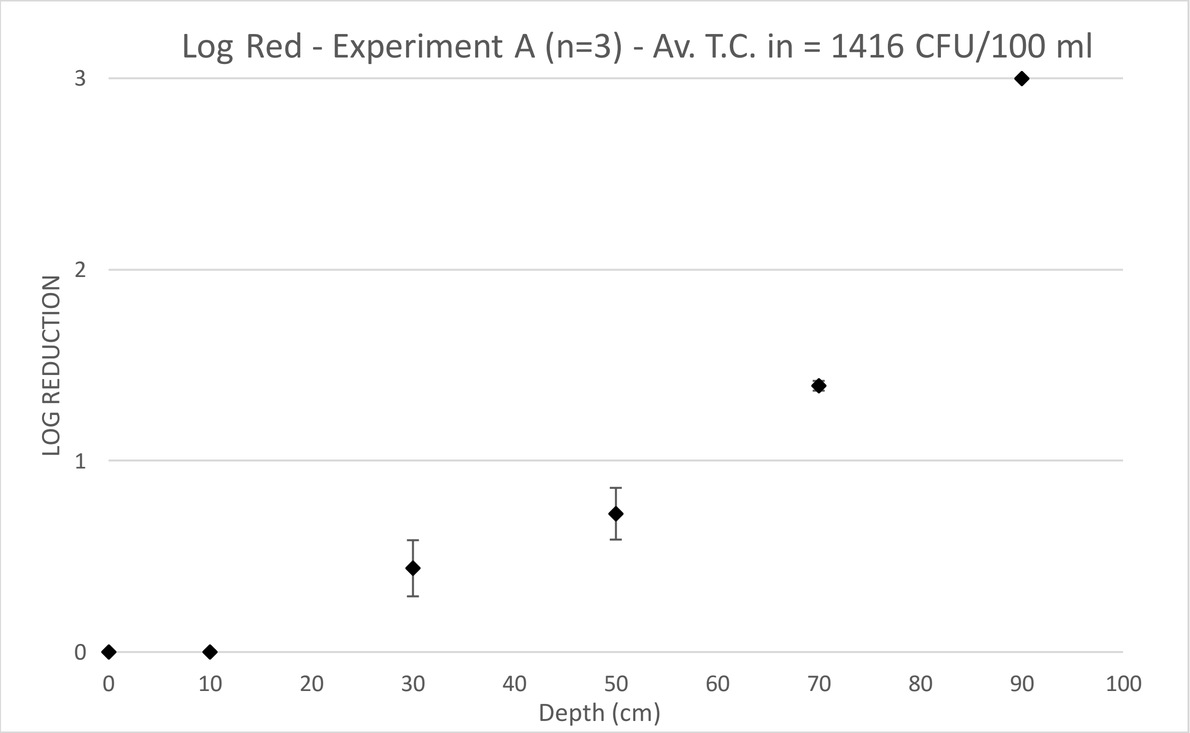


Figure 4-23. Log reduction of total coliform by column depth - experiment A

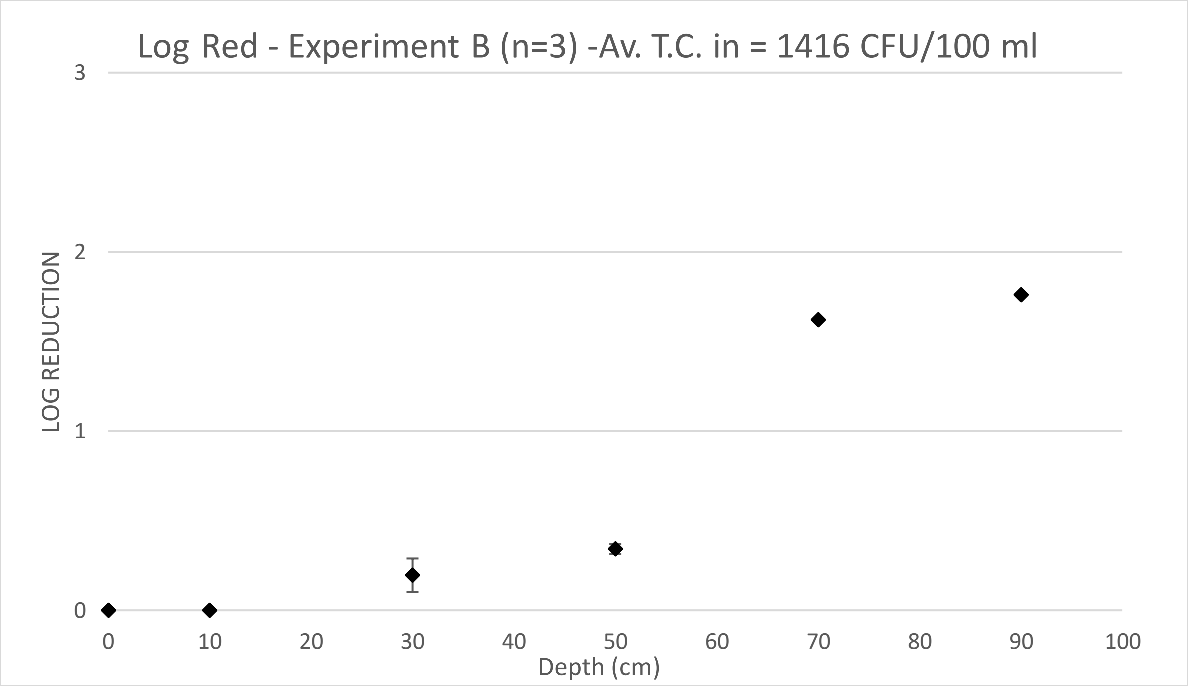


Figure 4-24: Log reduction of total coliform by column depth - experiment B

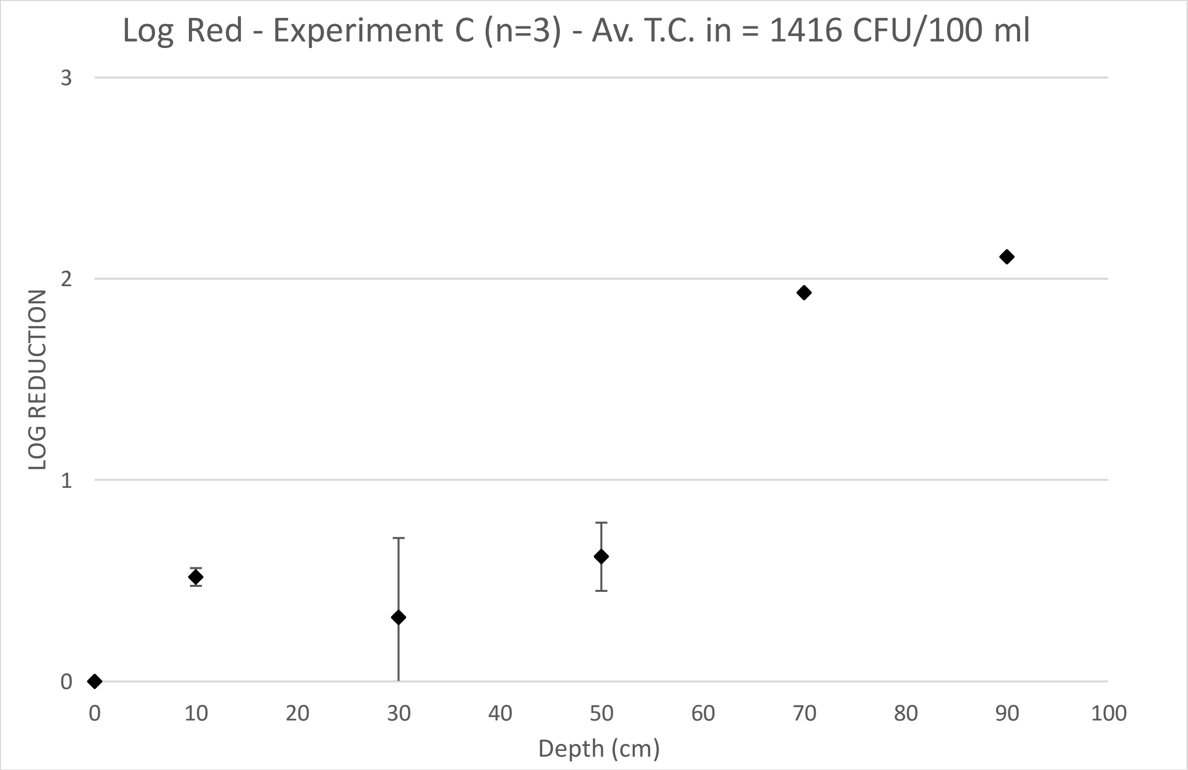


Figure 4-25: Log reduction of total coliform by column depth - experiment C

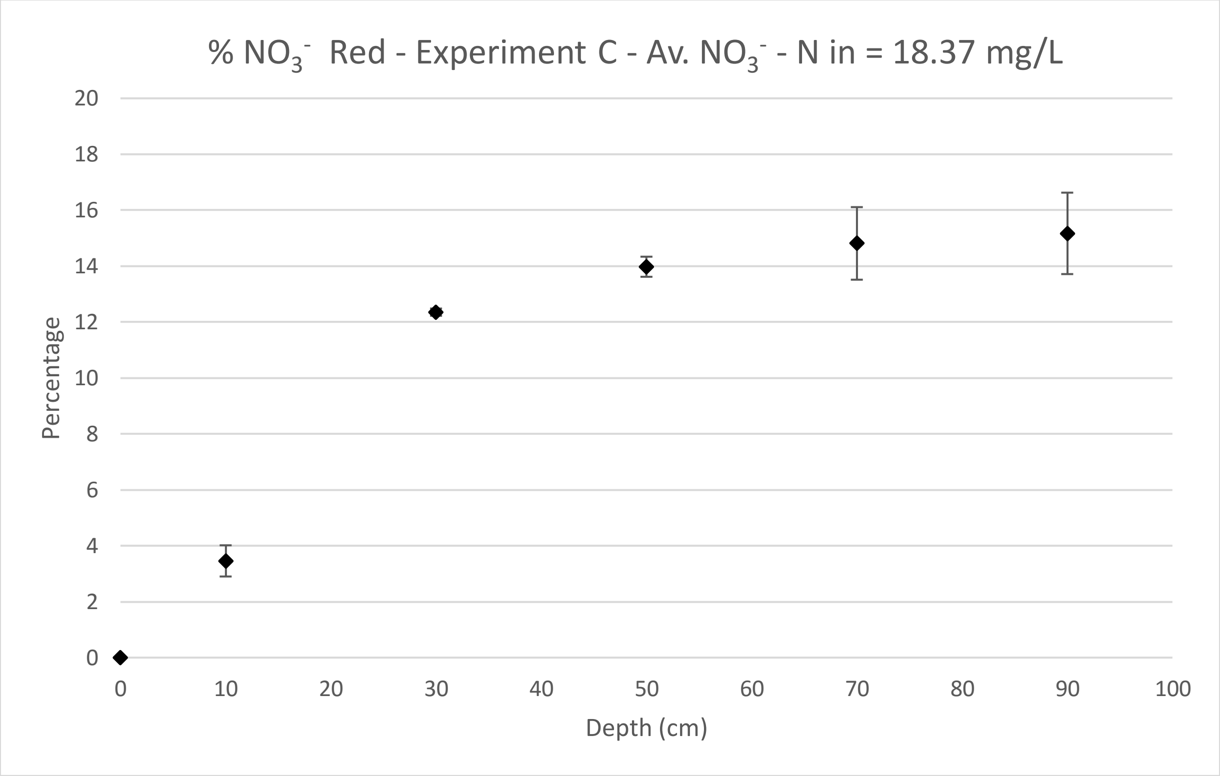
Biological contamination was measured by the removal of *E.coli* and total coliforms. Results show the removal of *E.coli* from secondary effluents occurs during the first 50 cm of the soil column and is not detected at the 90 cm depth for experiments A, B and C. Total coliforms reduction is also very high for experiments A, B and C. Most of the total coliforms removals for the experiments with secondary effluents occurs during the first 70 cm. The Ontario Drinking Water Standards, Objectives and Guidelines specifies non detectable concentrations of *E.coli* and total coliforms in drinking water sources.

4.4.1.4 Nitrogen removal

Final effluents from the APCP are mostly nitrified. Average TKN, Nitrate, free ammonia and un-ionized ammonia measured as nitrogen are 2 mg/L, 16.4 mg/L, 0.4 mg/L and 0.003 mg/L respectively (APCP, 2015). 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 acceptor. Reaction stoichiometry with biodegradable organic matter represented as $C_{10}H_{19}O_3N$ is shown below. However, DOC in secondary effluents is present is less biodegradable or non-biodegradable forms of carbon.

$$C_{10}H_{19}O_3N + 10\ NO_3^- \rightarrow 5N2 + 10\ CO_2 + 3H_20 + NH_3 + 10\ OH^-$$

Average nitrate concentration in inflow secondary effluents 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. Although oxygen is not completely consumed in the column effluent, heterotrophic denitrification can be explained by the formation of anaerobic zones in the soil due to the nature and complexity of porous media. Results are shown in figure 4-26.



Figures 4-26. Percentage Nitrate reduction by column depth

There are no guidelines 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. Average Nitrate concentration in secondary effluents is 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. Average nitrate consumption rates from experiment C normalized by the column section hydraulic retention time are shown in figure 4-27.

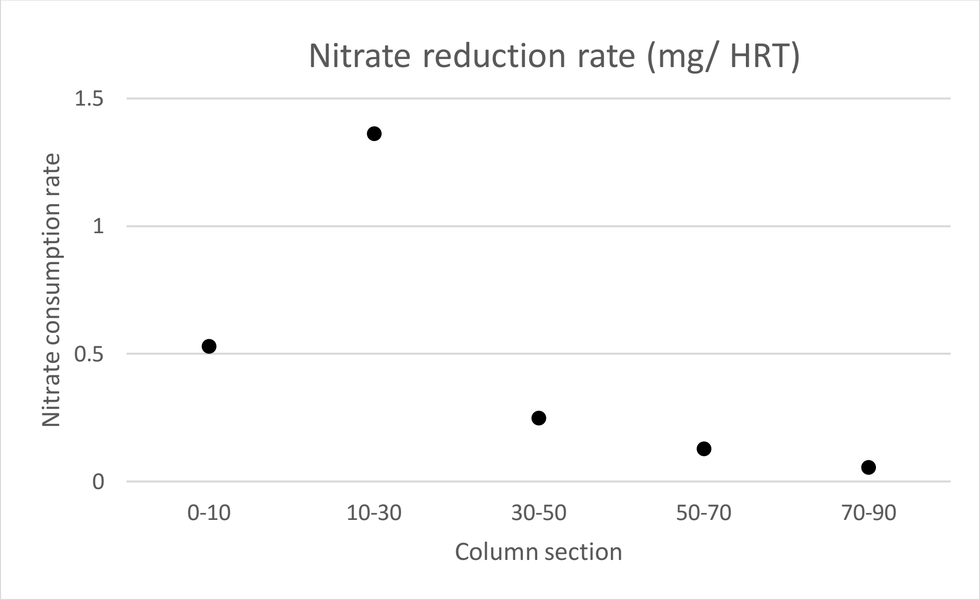


Figure 4-27: Nitrate consumption rate (mg/ HRT)

Nitrate removal efficiency by the SAT generally depends on the soil redox conditions and the availability of readily available organic matter for heterotrophic denitrification. Previous studies have shown that significant removal of nitrate is observed at sites where anoxic or anaerobic conditions are present (EPA, 2004).

Concentrations of orthophosphate and ammonia in the inflow secondary effluent from the APCP were below detectable levels at all column depths for all retention times. However, concentrations of orthophosphate and ammonia in the APPC secondary effluent were very low at 0.59 mg/L (SD=0.07) and 0.003 mg/L (SD= 0.001) respectively. Additionally, dissolved sulphate ions were measured as 41.87 mg/L (SD=3.23) in secondary effluents and no reductions were observed at any of the column depths for experiments A, B and C.

4.4.2 Soil aquifer treatment of simulated combined sewer overflows (Experiment D).

Combined systems carried sanitary and storms sewer simultaneously to the wastewater treatment plant to be treated. However, during storm events, the volume of stormwater collected by the combined sewer systems may exceed the treatment capacity of the wastewater plant, resulting in the release of untreated sewage into the local water ways. These CSO discharges are considered a significant source of pollution in the Great Lakes. An estimated 92 billion liters of CSOs are released into the Great Lakes in one year by cities in the Great Lakes basin (Ecojustice, 2013). Public and environmental health concerns with CSOs include biological contamination, organic compounds, heavy metals, toxic pollutants and oxygen depletion (US-EPA, 2011). During experiment D the SAT system was operated with simulated combined sewer overflows prepared in the laboratory by diluting raw wastewater with distilled water at a ratio of 1:2. Experiment D was run at a simulated hydraulic conductivity of 2.7 m/d.

4.4.2.1. Dissolved oxygen

Likewise experiments A, B and C, dissolved oxygen in the simulated CSOs was measured every day during the wetting cycle at inflow and outflow (90 cm). Average inflow DO in the simulated CSOs was measured as 5.9 mg/L (SD= 0.70) and average DO consumption at the last day of the wetting cycle was 51.50 %. Results are shown in figure 4-28.

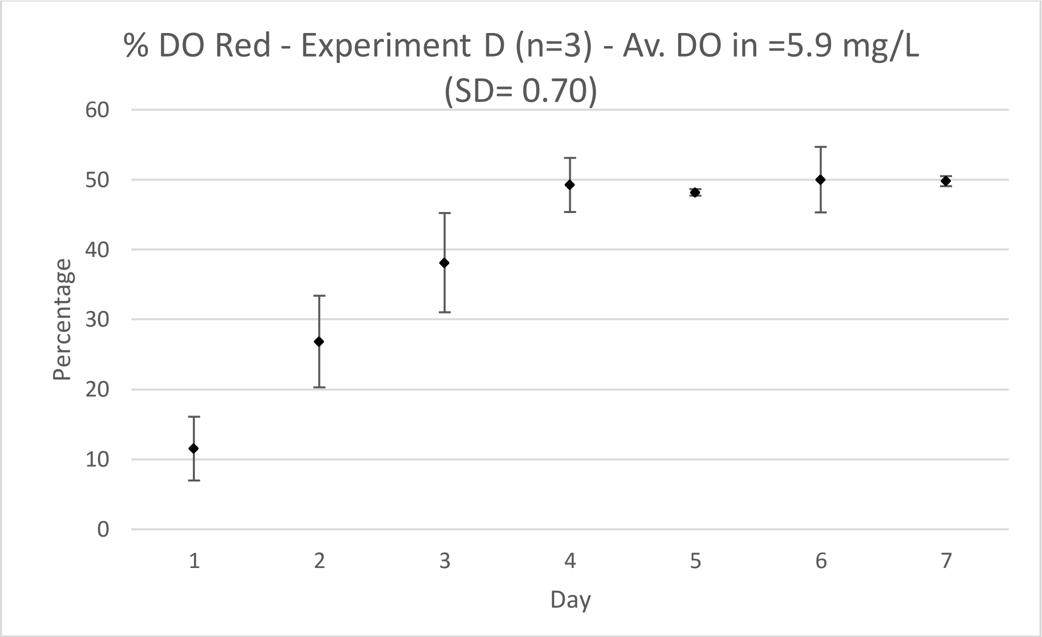


Figure 4-28: Average daily DO consumption (%) – 7 days wetting cycle

Additionally, samples taken from all the ports (0, 10, 30, 50, 70, 90 cm) on the 7 day of wetting were analyzed for dissolved oxygen. Average residual DO at the 90 cm depth was 3.01 mg/L with an average percentage DO consumption at the 90 cm depth of 51.50 %. Results are shown in figure 4-29. Average DO consumption rates normalized by the column section hydraulic retention time are shown in figure 4-30. Total DO consumed by the column in one HRT for experiment D is 2.59 mg/L.

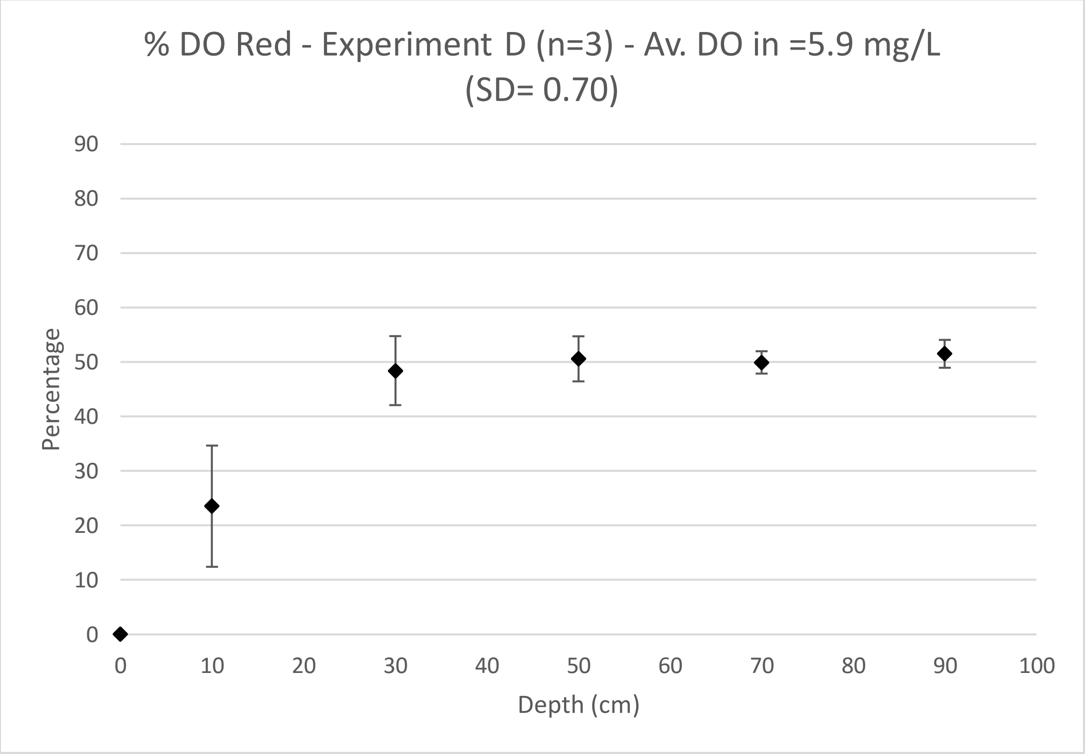


Figure 4-29. Percentage DO reduction by column depth - last day of wetting

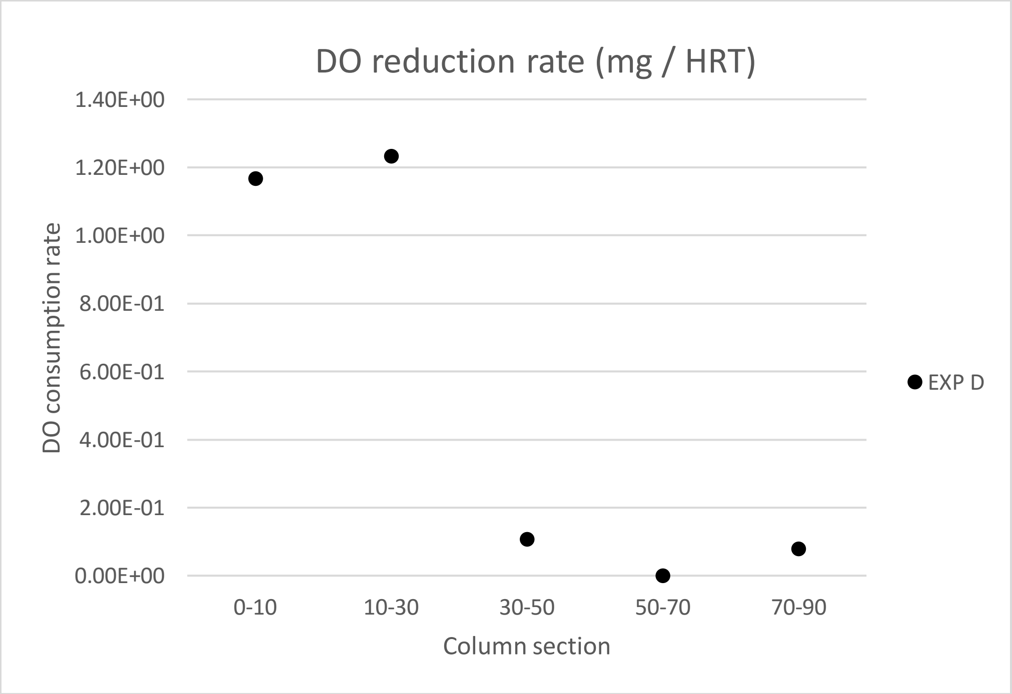


Figure 4-30. DO consumption rate (mg/ HRT)

Similar to the experiments with secondary effluent, results show that after 4 days of operation dissolved oxygen consumption does not change significantly for the remainder of the wetting cycle and 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. Unlike the experiments with secondary effluent, an average reduction of surface permeability by 31% was observed after 7 days of wetting. This is expected due to the presence of particulate and colloidal organic matter in raw wastewater.

4.4.2.2. Organic matter as BOD_5

Organic matter in CSOs was measured as BOD_5. Biodegradable organic matter in municipal wastewater is mainly found as carbohydrates, proteins and grease. Average BOD_5 in the simulated CSO was measured as 19.35 mg/L (SD=3.18). Results show the majority of BOD_5 removal occurs during the first 30 cm of the column and reaches a maximum of 54.26 % at the 90 cm depth. Results are shown in figure 4-31.

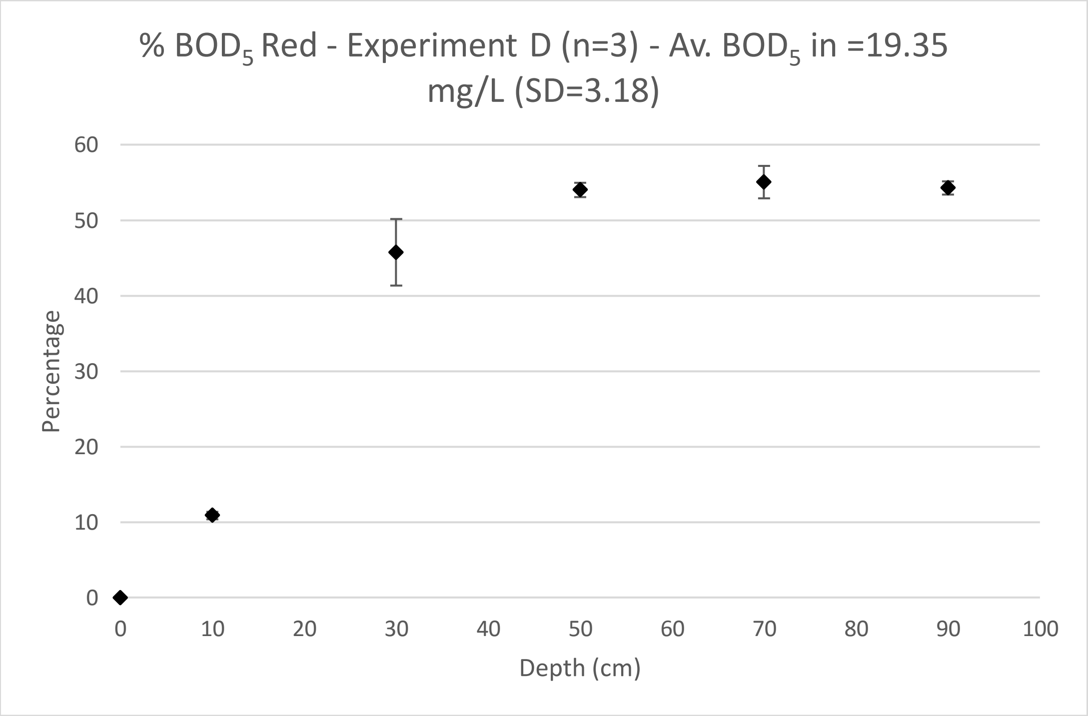


Figure 4-31: Percentage BOD_5 reduction by column depth - last day of wetting

Mechanisms of organic matter from CSOs by SAT is a combination of biodegradation, filtration and sorption processes. A positive correlation is observed between % DO consumption and % BOD_5 reduction for most of the curve which shows that BOD_5 reduction is mainly due to aerobic biological activity. See figure 4-32. Average BOD_5 consumption rates normalized by the column section hydraulic retention time are shown in figure 4-33. Total BOD_5 consumed by the column in one HRT for experiment D is 8.95 mg/L.

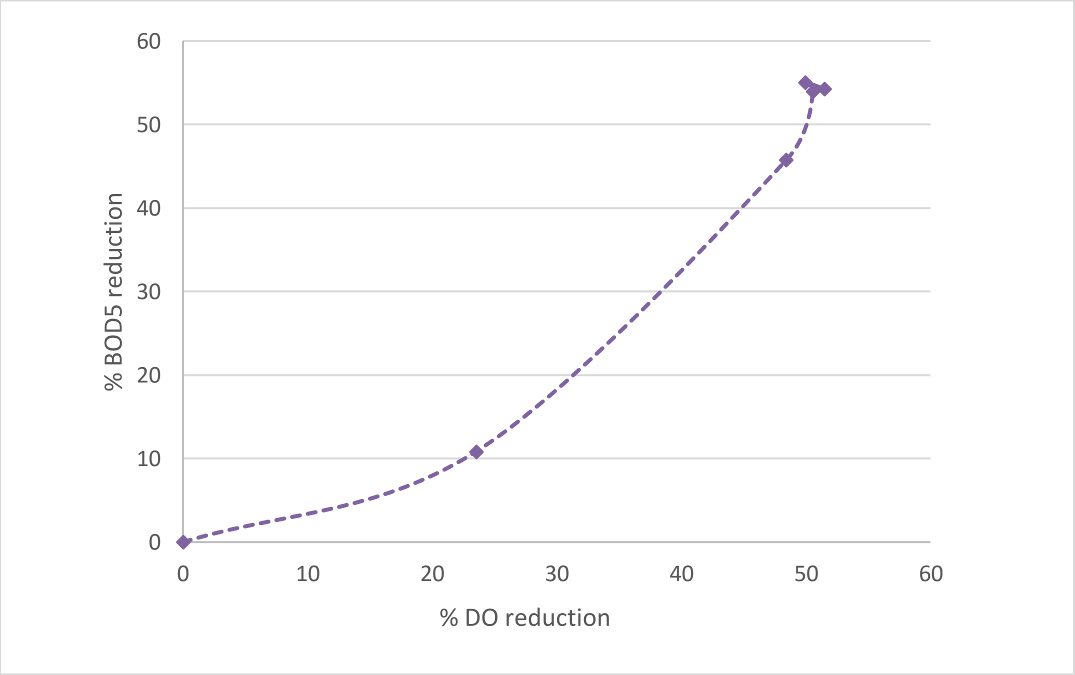


Figure 4-32: Average % BOD_5 reduction vs average % DO consumption – Experiment D

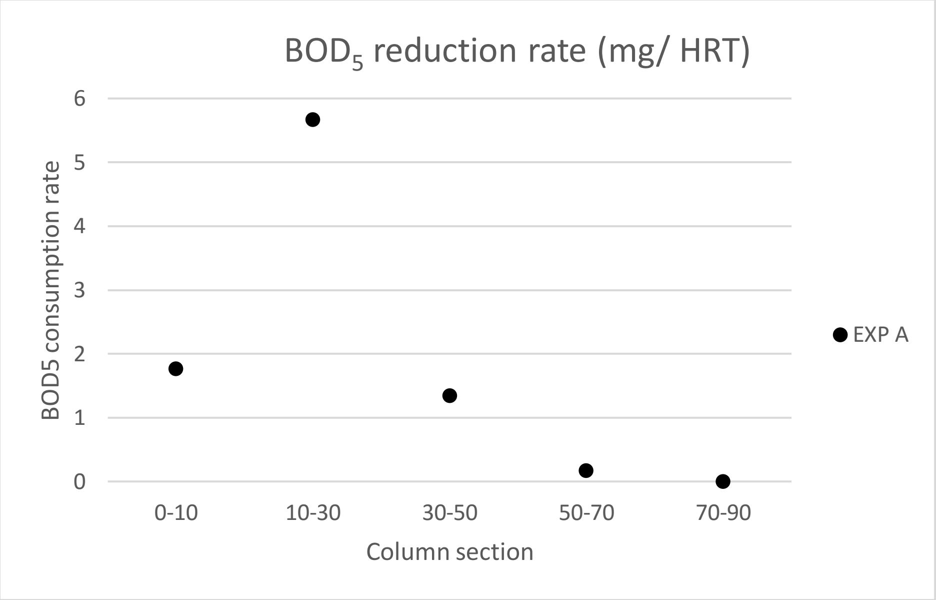


Figure 4-33: BOD$_5$ consumption rate (mg/ HRT)

Reduction rates vary significantly from the 0 to 10 cm to the 10 to 30 cm sections of the column compared to the DO reduction rate. This inconsistency may be explained by the presence of particulate organic matter and subsequent hydrolysis into a soluble form. While dissolved organic matter is consumed by aerobic biodegradation, it also produced by the hydrolysis of particulate organic matter. Although, 10.5 mg/L of BOD$_5$ were removed by the SAT system, only 3 mg/L of DO was removed. The high BOD$_5$ removal in comparison with DO, suggest that there is a large contribution of filtration and adsorption in the removal of particulate and dissolve organic matter in the simulated CSOs. Additionally, air diffused into the soil pores during the drying cycle also provides oxygen for biodegradation.

4.4.2.3 *E.coli* and total coliforms reduction.

Geometric mean *E.coli* and total coliform concentrations in the CSOs were measured as 750 CFU/100 ml and 6750 CFU/100 ml respectively. Removal of *E.coli* and total coliform concentrations were low with a maximum average reduction of log 0.2 and log 0.4

respectively at the 90 cm depth. Log reductions of *E.coli* and total coliform concentration are shown in figures 4-34 and 4-35.

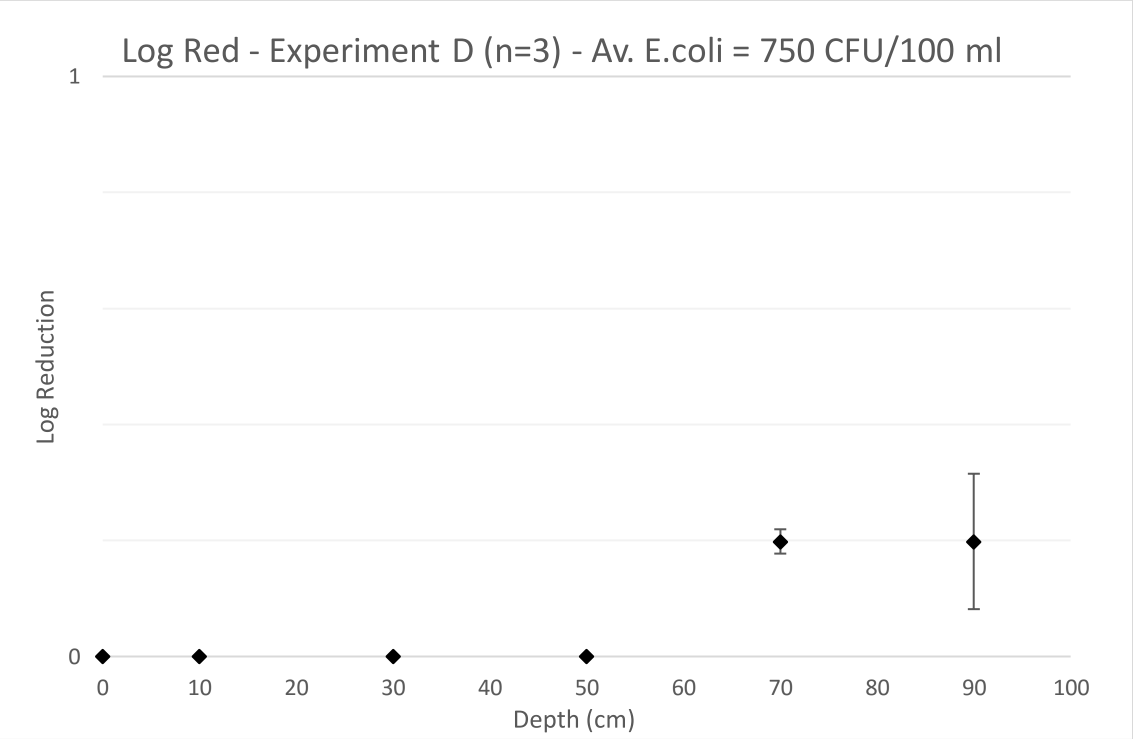


Figure 4-34: Log *E.coli* reduction by column depth - last day of wetting

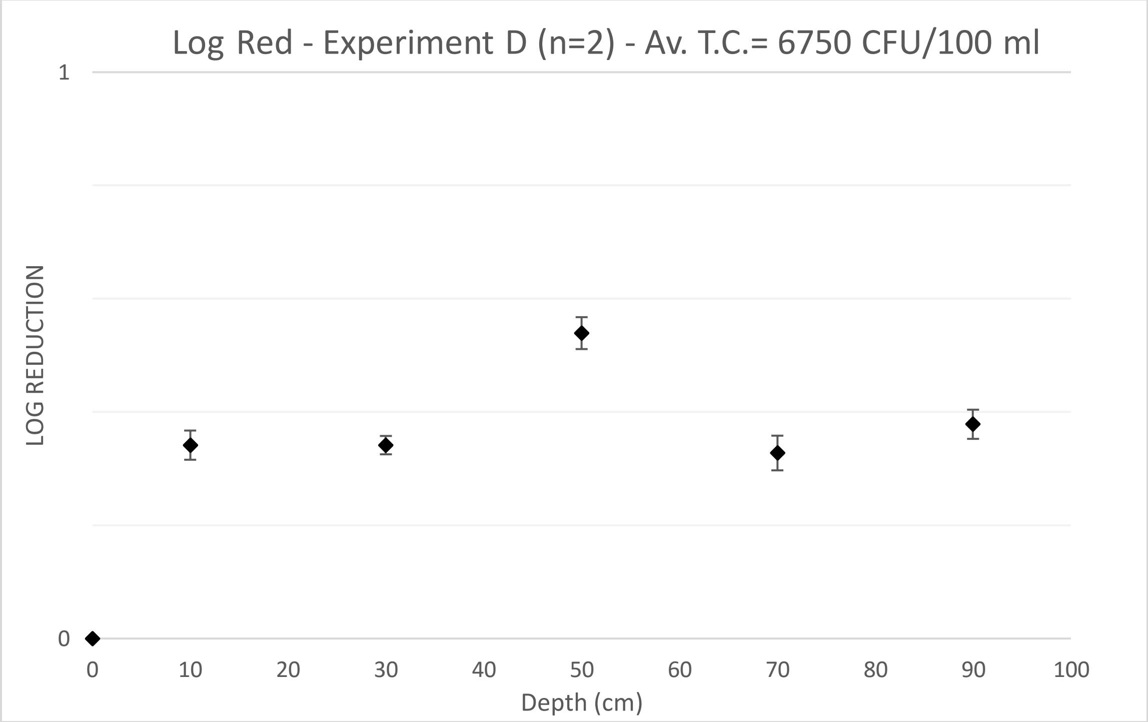


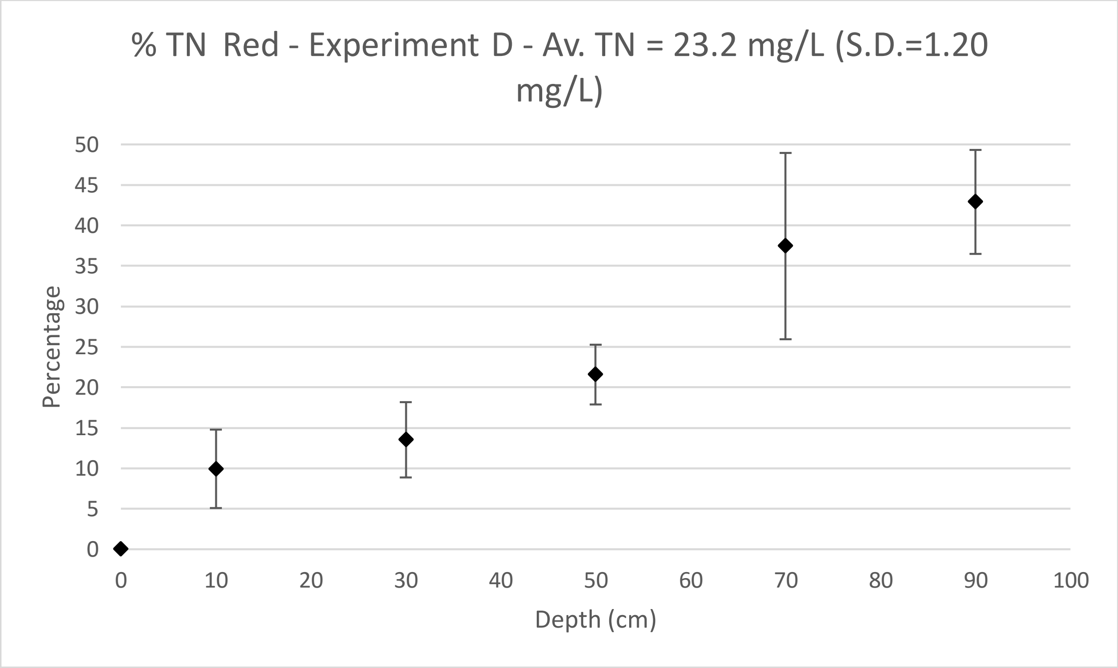
Figure 4-35. Log total coliforms reduction by column depth - last day of wetting

Biological contamination in CSOs was measured by the removal of *E.coli* and total coliforms. Results show that *E.coli* and total coliforms removal from CSOs are poor to moderate, reaching a maximum removal of log 0.2 and log 0.4 respectively at the 90 cm depth. Initial concentration of *E.coli* and total coliform are very high when compared with secondary effluents. The SAT system is not capable of removing the initial concentrations to acceptable levels for indirect potable aquifer recharge. The Ontario Drinking Water Standards, Objectives and Guidelines specifies non detectable concentrations of *E.coli* and total coliforms in drinking water sources.

4.4.2.4 Nitrogen removal from CSOs

Nitrogen removal from simulated combined sewer overflows was measured Total Nitrogen (TN). Nitrogen in the simulated CSOs is mainly present as ammonia and organic nitrogen.

Average total nitrogen in the simulated CSOs was measured as 23.2 mg/L (S.D.=1.20 mg/L) with an average removal of 42.9 % at the 90 cm depth. Results are shown in figure 4-36.



Figures 4-36: Percentage Total Nitrogen reduction by column depth

Nitrogen removal from simulated CSOs is mainly due to nitrification and adsorption. 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). Average TN consumption rates normalized by the column section hydraulic retention time are shown in figure 4-37. Total Nitrogen consumed by the column in one HRT for experiment D is 8.36 mg/L.

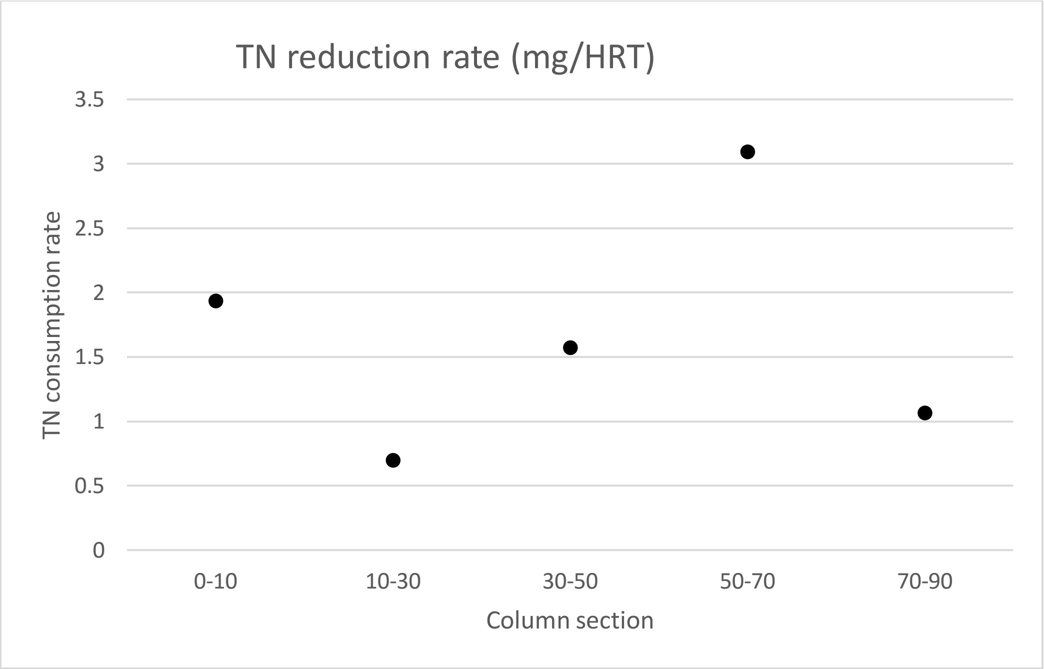


Figure 4-37. TN consumption rate (mg/ HRT)

4.4.3 Soil Aquifer Treatment with enhance nitrate removal from secondary effluents (Experiments E to J)

During the experiments with secondary effluent a low removal of Nitrates was observed. reaching a maximum removal of 15.17 % at the longest hydraulic retention time. Nitrate ions were not removed at experiments A and B, and only slightly removed (15.17 %) at experiment C. Denitrification is generally limited by the column redox conditions and the availability of organic matter. Consequently, in order to improve denitrification, readily available organic matter was added to the secondary effluents at methanol/glucose: NO_3^--N ratios of 1:1, 3:1 and 6:1 and operated at a HRT of 2.8 hours. Average nitrate concentration in inflow secondary effluents was measured as 18.37 mg/L NO_3^- - N (SD=4.04 mg/L). Two sources of carbon were used: methanol and glucose.

4.4.3.1. Methanol

A wide range of carbon sources can be used to meet the soluble COD needs for denitrification. Commonly used sources of external carbon include methanol, ethanol, acetate, acetic acid, glycerol, molasses sugar water and proprietary formulations (US-EPA, 2013). Methanol has been commonly employed as external carbon source due to being easily assimilated by denitrifying bacteria and its low cost (Peng et al., 2007; Fernández-Nava et al., 2010). Blue Plains wastewater treatment plant that serves the greater Washington D.C. area with a flow of 370 million gallons per day, reported methanol denitrification cost as \$0.50 - \$0.60 per pound of nitrogen removed (MI, 2011).

Reaction stoichiometric when methanol is the carbon source is as follows:

$$5CH_3OH + 6\ NO_3^- \Rightarrow 3N_2 + 5CO_2 + 7\ H_2O + 6\ OH^-$$

The stoichiometry of this reaction indicates that for each gram of nitrate-nitrogen that is reduced, 1.9 grams of methanol are needed. However, in practice, methanol to NO_3-N dose ratios are in the range of 2 to 3.5 g methanol/ g NO_3-N at 20 ^oC (EPA, 1970; Tchobanoglous et al., 2003). Therefore, between 36.7 to 64.3 mg/L of methanol are required to denitrify the average nitrate concentration in the secondary effluents. Three different methanol: NO_3^- -N ratios where 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 figures 4-38 to 4-40.

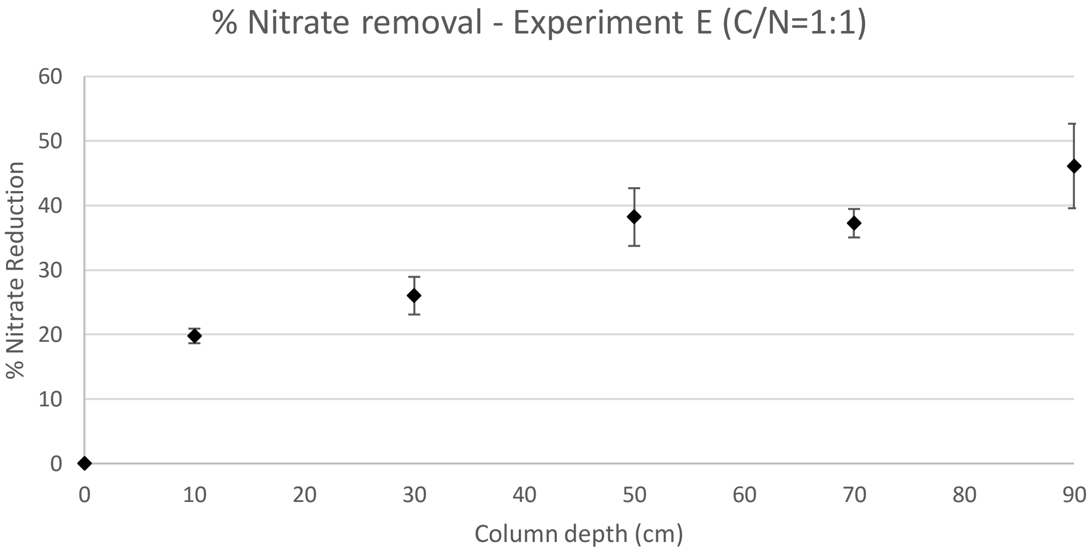


Figure 4-38: Percentage Nitrogen reduction from secondary effluents by column depth - experiment E

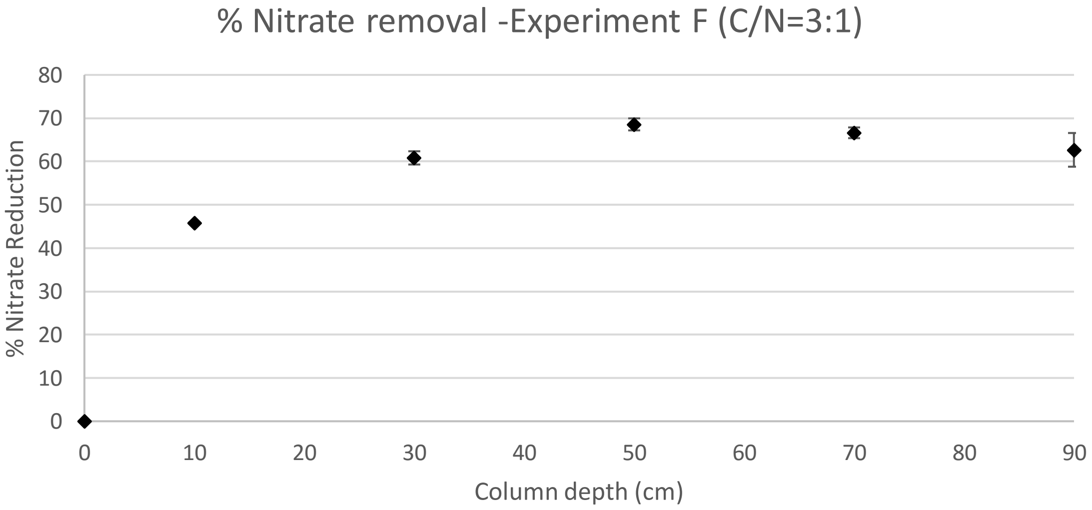


Figure 4-39: Percentage Nitrogen reduction from secondary effluents by column depth - experiment F

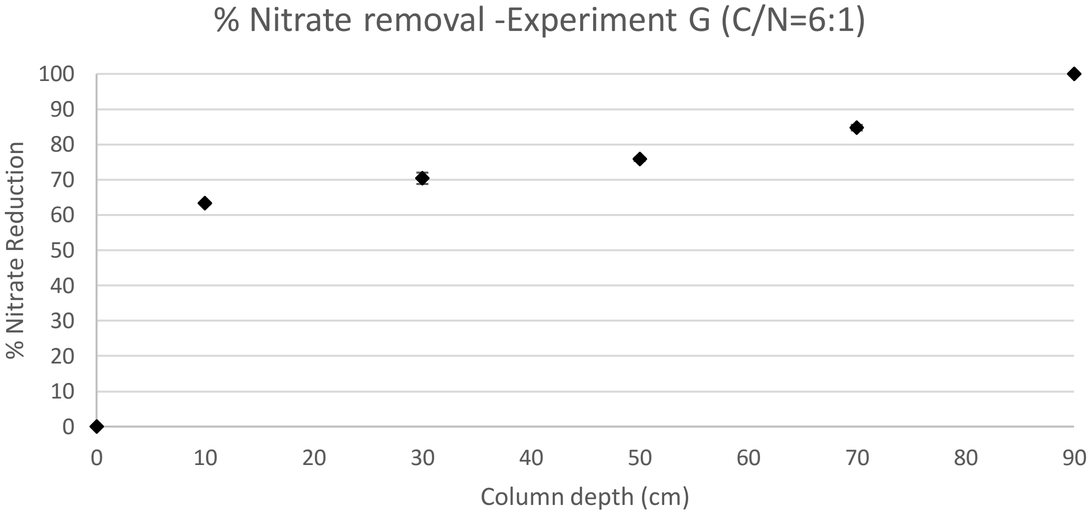


Figure 4-40: Percentage Nitrogen reduction from secondary effluents by column depth - experiment G

Issues with methanol addition to wastewater to improve denitrification include cost volatility and safety concerns. Several carbon sources such as glycerin-based products derived from biodiesel production, as well as several sugar-based waste products from the food and beverage industry are viewed as promising, more sustainable replacements for methanol (Bilyk et al., 2010). However, denitrifying organisms grown on carbohydrate solutions result in a higher biomass yield which can create operational challenges.

4.4.3.2 Glucose

The second source of carbon used to promote denitrification was glucose. Glucose has the potential of sustainably enhancing denitrification and, unlike methanol, it is nonhazardous. Reaction stoichiometric when glucose is the carbon source is as follows:

$$0.21\ C_6H_{12}O_6 + NO_3^- + H_2O \ \text{--->}\ 0.5\ N_2 + 1.25\ CO_2 + 1.75\ H_2O + OH^-$$

The stoichiometry of this reaction indicates that for each gram of nitrate-nitrogen that is reduced, 2.68 grams of glucose are needed. In practice, a C/N ratio of 5:1 for complete denitrification has been reported (Naik and Setty, 2012). Therefore, between 91.85 mg/L of glucose are required to denitrify the average nitrate concentration in the secondary effluents. Three different glucose: NO_3^- -N ratios where investigated, 1:1, 3:1 and 6:1, in experiments H, I and J 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 32.06 % (1:1), 59.10 % (3:1) and 88.53 % (6:1) was achieved at the 90 cm depth. Results are shown in figures 4-41 to 4-43.

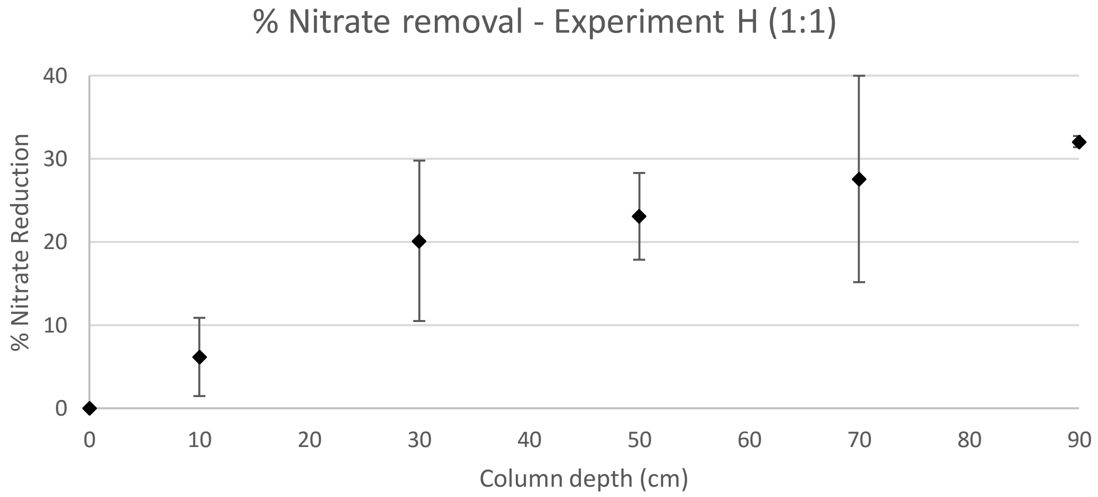


Figure 4-41: Percentage Nitrogen reduction from secondary effluents by column depth - experiment H

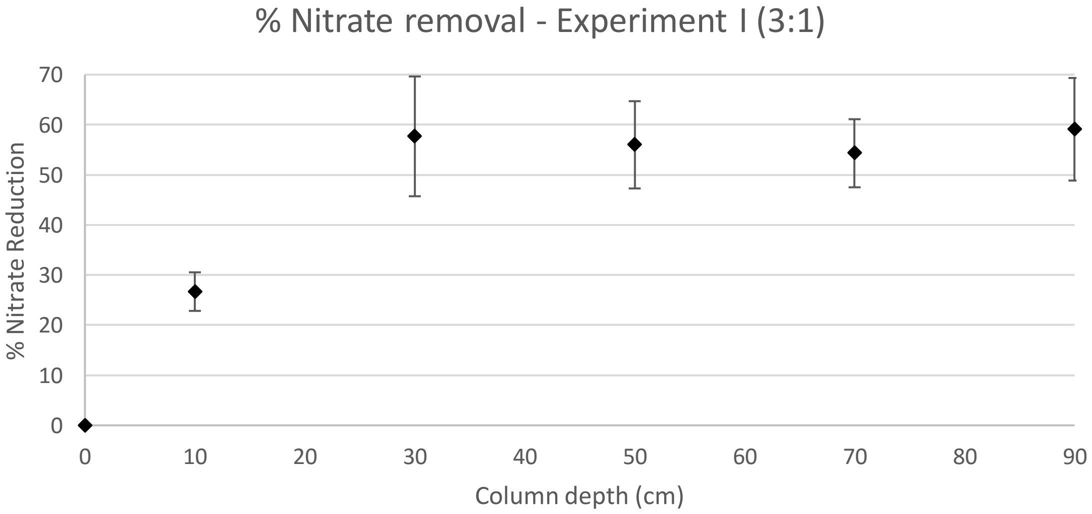


Figure 4 -42: Percentage Nitrogen reduction from secondary effluents by column depth -experiment I

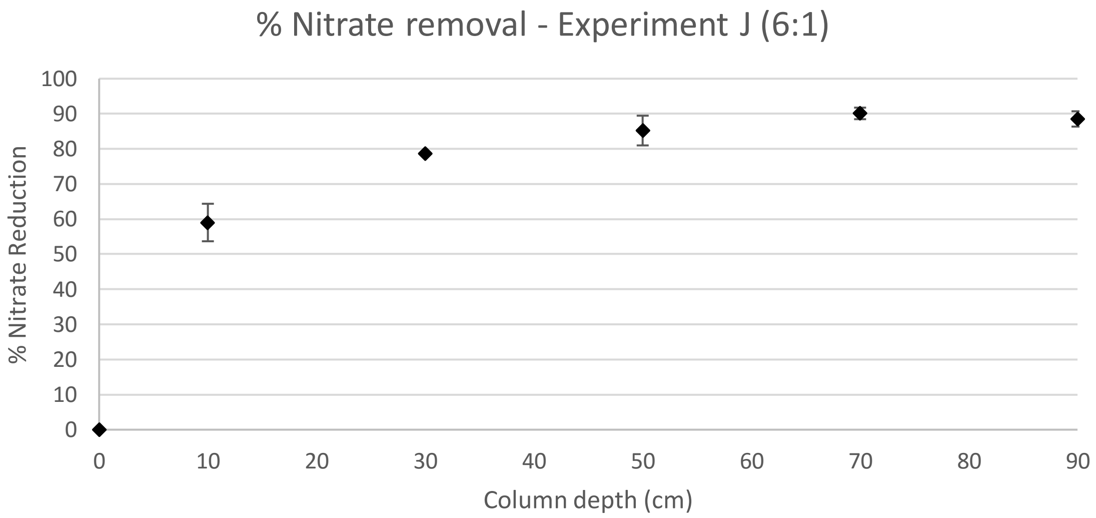


Figure 4-43. Percentage Nitrogen reduction from secondary effluents by column depth - experiment J

Results show nitrate removal is significantly enhanced by the addition of readily available organic matter. Added readily available organic matter provides energy for the reduction of nitrate and also for the production of biomass. As a result, more organic matter is required than the calculated based on stoichiometry. The amount of new biomass generated and the portion used for denitrification are specific to each compound. These findings highlight the importance of protecting recharge wetlands in regions with high permeability soils since they can provide the additional organic matter needed for denitrification.

4.5 Conclusions

The prevalent high permeability soils of southwestern Ontario are fine to medium grained sand grains with hydraulic conductivities ranging from 1 to 20 m/d. Experiments with secondary effluents showed that oxygen consumption during the wetting cycle is proportional to the hydraulic retention time and 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. Oxygen consumption rates also consistently decrease as the depth of the soil increases for all hydraulic retention times. 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.

DOC removal by the laboratory scale SAT system was low, reaching a maximum of 22.81 % at the longest retention time. This low DOC removal is explained by the high hydraulic conductivity of high permeability soils and the nature of organic carbon in secondary effluents, which is mainly composed of non-readily biodegradable carbon such as natural organic matter, soluble microbial products and emergent contaminants. Removal of DOC from secondary effluents showed dependency on both retention time and column depth up to approximately 50 cm. Correlations are observed between % DO consumption and % DOC reduction shows DOC removal due to biodegradation and adsorption for the first 30 cm of the column and predominantly adsorption between 50 to 90 cm depth. In experiment C, organic matter is also consumed for heterotrophic denitrification. DOC reduction rates are also higher during the first 50 cm of the column with some unexpected variability that can be explained by the competing processes of biodegradation and adsorption. Characterization of organic matter forms in secondary effluents DOC is necessary to determine its theoretical oxygen demand.

E.coli was not detected at the 90 cm depth at all hydraulic retention times and most of the removal occurs during the first 50 cm of the soil column. At least a log 3 removal is achieved by the SAT system. Likewise, total coliforms were almost completed removed at the 90 cm depth at experiments A (> log 3), B (log 1.7) and C (log 2.1).

Nitrate removal from secondary effluents by SAT was slightly achieved at the longest retention time of 13.9 hours with an average 15.17 % reduction the 90 cm depth. Although oxygen is not completed consumed in the column effluent, heterotrophic denitrification can be explained by the formation of anaerobic zones in the soil due to the nature and complexity of porous media. After a 15.17% removal, nitrate concentration is still higher than the accepted limit of the Ontario Drinking Water Standards, Objectives and Guidelines. No reductions in hydraulic conductivity was detected due to column clogging.

The experiments with simulated CSOs, showed the largest DO reduction occurs during the first 30 cm of the soil column, which is attributed to higher biological activity of heterotrophic bacteria in the aerobic zone of the column. Oxygen consumption rates also consistently decrease as the depth of the soil increases for all hydraulic retention times. Unlike the experiments with secondary effluent, an average reduction of surface permeability by 31% was observed after 7 days of wetting.

The majority of BOD_5 removal occurs during the first 30 cm of the column and reaches a maximum of 54.26 % at the 90 cm depth. Mechanisms of organic matter from CSOs by SAT is a combination of biodegradation, filtration and adsorption processes. A positive correlation is observed between % DO consumption and % BOD_5 reduction for most of the curve which shows that BOD_5 reduction occurs due to aerobic biological activity. The high BOD_5 removal in comparison with DO reduction, suggests that there is a large contribution of filtration and adsorption in the removal of particulate and dissolve organic matter in the simulated CSOs.

Removal of *E.coli* and total coliform concentrations from CSOs were low with a maximum average reduction of log 0.2 and log 0.4 respectively at the 90 cm depth. Total nitrogen removal from simulated CSOs was moderate (42.9 %) and mainly due to nitrification and adsorption. Ammonia is consumed by a combination volatilization and adsorption with subsequent nitrification during the drying cycle.

Methanol and glucose addition showed that denitrification of secondary effluents greatly improves when readily available organic matter is provided. 100 % and 88.53 % removals of Nitrate were achieved at a ratio of 6:1 for methanol and glucose respectively. This is consistent with previous studies and provides scientific support for the importance of protecting recharge wetlands for groundwater quality protection in southwestern Ontario since they can provide additional organic matter needed for denitrification.

In summary, high permeability soils of southwestern Ontario, have the ability to polish secondary effluents in terms of DOC, *E. coli* and total coliforms. However, issues with the persistence of nitrates affects its suitability for potable aquifer recharge. Therefore, polished secondary effluent from the APCP by SAT will be more suitable for non-potable groundwater recharge. Recharge of potable aquifers may also be a possibility if wastewater effluents are de-nitrified. Regarding 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.

Even though the removal of *E.coli* and total coliforms from secondary effluents were very high, disinfection is still recommended for the inactivation of viruses and protozoa. There are also concerns with the long-term effects on human health from exposure to contaminants such as pharmaceuticals and personal care products.

It is important to understand that we are currently engaging in de-facto indirect potable reuse by discharging wastewater effluents into the Great Lakes and its tributaries. Therefore, it is essential to investigate if current wastewater effluent regulations are adequate for the protection of human and environmental health.

4.6. References

Abel C., Sharma S., Mersha S. and Kennedy M. Influence of intermittent infiltration of primary effluent on removal of suspended solids, bulk organic matter, nitrogen and pathogens indicators in a simulated managed aquifer recharge system. Ecological Engineering. Volume 64, March 2014, Pages 100–107.

Ak M. and Gunduz O. Comparison of Organic Matter Removal from Synthetic and Real Wastewater in a Laboratory-Scale Soil Aquifer Treatment System. Water Air Soil Pollution (2013) 224:1467.

American Water Works Association – Research Foundation (AWWA-RF). Soil Aquifer Treatment for Sustainable Water Reuse. 2001. ISBN 1-58321-113-0.

American Water Works Association – Research Foundation (AWWA-RF). Soil Treatability Pilot Studies to Design and Model Soil Aquifer Treatment Systems. 1998. ISBN 0-898679-11-7.

Bateman E.J., Baggs E.M., 2005. Contributions of nitrification and denitrification to N_2O emissions from soils at different water- filled pore space. Biology and Fertility of Soils 41 (6), 379e388.

Bouwer H. Groundwater Hydrology. New York. McGraw-Hill. 1978.

Bouwer H. Artificial recharge of groundwater: hydrogeology and engineering. Hydrogeology Journal (2002) 10:121–142

Bilyk K., Bruton T and Rohrbacher J. Finding flexibility in carbon supplementation: Lessons from four plants. Horizons 2010. Hazen and Sawyer environmental engineers and scientist. http://www.hazenandsawyer.com (accessed August 2016)

Cha W., Choi H., Kim J. and Cho J. Water quality dependence on the depth of the vadose zone in SAT-simulated soil columns. Water Science and Technology: Water Supply Vol 5 No 1 pp 17–24 © IWA Publishing 2005.

Cha W., Choi H., Kim J., and Kim, I. (2004) Evaluation of wastewater effluents for soil aquifer treatment in South Korea. Water Science and Technology, 50(2), 315- 322.

Chapman L and Putnam D. The physiography of southern Ontario. Ontario Ministry of Natural Resources, 1984. 3rd ed.

City of London. Environmental and engineering services. Wastewater treatment operations division. 2014. https://www.london.ca/residents/Sewers-Flooding/Sewage-Treatment/Documents/SEWAGE-Mar14.pdf (accessed Oct 2015)

City of London. 2014 Annual Report. Adelaide Wastewater Treatment Plant. February 2015. Environmental and Engineering Services Department. Wastewater Treatment Operations. https://www.london.ca/residents/Sewers-Flooding/Sewage-Treatment/Documents/ADELAIDE14-AODA.pdf (accessed June 2015).

Dillon P., Pavelic P., Toze S., Rinck-Pfeifferb S., Martinc R., Knaptond A. and Pidsleye D. Role of aquifer storage in water reuse. Desalination 188 (2006) 123–134.

Drewes J., Heberer T and Reddersen K. Fate of pharmaceuticals during indirect potable reuse. Water Science and Technology. 2002, 46 (3) 73-80.

Drewes J.E., and Fox P. 1999. Fate of natural organic matter (NOM) during groundwater recharge using reclaimed water. Water Science and Technology. 40(9):241–248.

Ecojustice. The Great Lakes Sewage Report Card 2013. http://www.ecojustice.ca/wp-content/uploads/2014/08/FINAL-The-Great-Lakes-Sewage-Report-Card-2013.pdf (accessed Sept 2015)

Essandoh H.M.K, Tizaouib C., Mohameda M.H.A. Removal of dissolved organic carbon and nitrogen during simulated soil aquifer treatment. Volume 47, Issue 11, 1 July 2013, Pages 3559–3572.

Essandoh H.M.K, Tizaouib C., Mohameda M.H.A, Amy G. and Brdjanovic D. Soil aquifer treatment of artificial wastewater under saturated conditions. Water Research 45 (2011) 4211 -4226.

Exall C., Marsalek J. And Schaefer K. Water Reuse in Canada: Opportunities and Challenges. National Water Research Institute, Environment Canada. In P. Hlavinek et al (eds), Integrated Urban Water Resources Management, 253 – 262. 2006 Canadian Crown. Printed in Netherlands.

Fernández-Nava, Y., Marañón, E., Soons, J., & Castrillón, L. (2010). Denitrification of high nitrate concentration wastewater using alternative carbon sources. Journal of Hazardous Materials, 173(1), 682-688.

Fox P., Aboshanp, W., and Alsamadi, B. Analysis of Soils to Demonstrate Sustained Organic Carbon Removal During Soil Aquifer Treatment. 2005. Environmental Quality, 34, 156-163.

Gao, H., Schreiber, F., Collins, G., Jensen, M.M., Kostka, J.E., Lavik, G., de Beer, D., Zhou, H.Y., Kuypers, M.M.M., 2010. Aerobic denitrification in permeable Wadden Sea sediments. ISME Journal 4 (3), 417e426.

Gandhi R., Ray A., Sharma V and Nakhla G. Treatment of Combined Sewer Overflows Using Ferrate (VI). Water Environment Research, Volume 86, Number 11.

Government of Canada. Wastewater Systems Effluent Regulations (WSER). SOR/2012-139. Fisheries Act. 2012. http://laws-lois.justice.gc.ca/eng/regulations/SOR-2012-139/FullText.html (accessed Nov 2015).

Guizani M., Kato H. and Funamizu N. Assessing the removal potential of soil-aquifer treatment system (soil column) for endotoxin. J. Environ. Monit., 2011, 13, 1716.

Haddad B., Rozin P., Nemeroff C. and Slovic P. The psychology of water reclamation and reuse : Survey findings and research road map. Water Reuse Foundation, 2009.

Harun, C.M. (2007) Analysis of multiple contaminants during soil aquifer treatment. UNESCO-IHE MSc thesis No MWI-2007-18.

He, K., Echigo, S. and Itoh, S. Effect of operating conditions in soil aquifer treatment on the removals of pharmaceuticals and personal care products. 2016. Science of the Total Environment. Volume: 565 Pages: 672-681

Health Canada. Guidelines for Canadian Drinking Water Quality. http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/sum_guide-res_recom/index-eng.php#t2 (accessed Nov 2015)

Jimenez Blanca and Asano Takashi. Water Reuse. An international survey of current practice, issues and needs. 2008. IWA publishing.

Lishman L., Smyth S.A., Sarafin K., Kleywegt S., Toito J., Peart T., Lee B., Servos M., Beland M and Seto P. Occurrence and reductions of pharmaceuticals and personal care products and estrogens by municipal wastewater treatment plants in Ontario, Canada. Science of the Total Environment 367 (2006) 544–558

Methanol Institute (MI). Methanol and Wastewater Denitrification. 2011 http://www.methanol.org/ (accessed August 2016)

Ministry of Environment (MOE), Amended Environmental Compliance Approval Number 7397-96SPH7. Issue Date: April 17, 2013. https://www.accessenvironment.ene.gov.on.ca/instruments/0206-96SH3W-14.pdf (accessed Nov. 2015).

Naik. S and Setty Y. Biological denitrification of wastewater-A Mini Review on Carbon Source. International Conference on Chemical, Environmental Science and Engineering (ICEEBS'2012) July 28-29, 2012 Pattaya (Thailand)

National Research Council (NRC) of the national academics. Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater. National Academy of Sciences. 2012. ISBN: 978-0-309-25749-7.

National Center for Sustainable Water Supply (NCSWS). Investigation on Soil-Aquifer Treatment for sustainable water reuse. 2001. Arizona State University. www.eas.asu.edu/~civil/ncsws/NCSWS.html (accessed February, 2016)

Northeast Region Certified Crop Adviser (NRCCA) Study Resources. Soil Hydrology AEM. 2010. Cornell University. https://nrcca.cals.cornell.edu/soil/CA2/CA0212.1-3.php (accessed August, 2016)

Onesions K. and Bouwer E. Biological removal of pharmaceuticals and personal care products during laboratory soil aquifer treatment simulation with different primary substrate concentrations. Water Research 46 (2012) 2365 e 2375.

Ontario Geological Survey (OGS). 2010. Surficial geology of Southern Ontario; Ontario Geological Survey, Miscellaneous Release--Data 128-REV. ISBN 0-7794-5298-4 (set); ISBN 0-7794-5299-2 (v.1); ISBN 0-7794-5300-X (v.2).

Peng, Y., Ma, Y., & Wang, S. (2007). Denitrification potential enhancement by addition of external carbon sources in a pre-denitrification process. Journal of Environmental Sciences, 19(3), 284-289.

Quanrud, D. M., Arnold, R. G., Lansey, K. E., Begay, C., Ela, W., and Gandolfi, A. J. (2003) Fate of effluent organic matter during soil aquifer treatment: biodegradability, chlorine reactivity and genotoxicity. Journal of Water and Health, 1(1), 33-45.

Region of Waterloo. 2010. Potable Groundwater Criteria Use in the Region of Waterloo. http://www.regionofwaterloo.ca/en/abouttheenvironment/resources/wp_potable_water_policy.pdf (accessed Dec 2015)

Rodriguez C., Van Buynder P., Lugg R., Blair P., Devine B., Cook C. and Weinstein P. Indirect Potable Reuse: A Sustainable Water Supply Alternative. International Journal of Environmental Research and Public Health, 2009, 6, 1174-1209.

Sharma S., Harun C. and Amy G. Framework for assessment of performance of soil aquifer treatment systems. Water Science & Technology—WST, 57.6, 2008.

Ontario Drinking Water Standards, Technical Support Document, Objectives and Guidelines. 2003. Revised June 2006. https://dr6j45jk9xcmk.cloudfront.net/documents/1140/81-drinking-water-standards-objectives-and.pdf (accessed Nov 2015)

Trevors J. The influence of oxygen concentrations on denitrification in soil. Applied Microbiology and Biotechnology (1985)23:152—155.

Tchobanoglous, G., Burton, F. L., and Stensel, D. H. (2003). Wastewater Engineering, Treatment, and Resuse, McGraw Hill, New York.

US Environmental Protection Agency (US-EPA). Wastewater Treatment Fact Sheet: External Carbon Sources for Nitrogen Removal. 2013. https://nepis.epa.gov (accessed August, 2016)

Velasquez D. and Yanful E.K. Water reuse perceptions of students, faculty and staff at Western University, Canada. Journal of water reuse and desalination. IWA Publishing 2015.

Wentworth, Chester K. A Scale of Grade and Class Terms for Clastic Sediments. The journal of geology, Volume 30. No. 5 (Jul. - Aug., 1922), pp. 377-392.

Westerhoff, P., and Pinney, M. (2000) Dissolved organic carbon transformations during laboratory-scale ground water recharge using lagoon-treated wastewater. Waste

Management, 20(1), 75-83.

Wintgens T., Salehi F., Hochstrat R. and Melin T. Emerging contaminants and treatment options in water recycling for indirect potable use. Water Science & Technology—WST, 57.1, 2008.

Upper Thames River Conservation Authority (UTRCA). Upper Thames River Assessment Report: Municipal Drinking Water System Summary - City of London Water Supply System. 2011. http://www.sourcewaterprotection.on.ca (Accessed May 2014)

US - Environmental Protection Agency (US-EPA), Guidelines for Water Reuse, Technology Transfer and Support Division, National Risk Management Research Laboratory. 2004.

US - Environmental Protection Agency (US-EPA). Keeping Raw Sewage & Contaminated Stormwater Out of the Public's Water. 2011. http://www.epa.gov/region02/water/sewer-report-3-2011.pdf (accessed Sept 2015)

US - Environmental Protection Agency (EPA). Water Quality Office. Methanol requirement and temperature effects in wastewater denitrification. 1970. http://www3.epa.gov/ (accessed Nov, 2015).

Chapter 5

5. Conclusions

Wastewater reclamation is becoming an increasingly important alternative for sustainable water resources management in many regions around the world. It is mainly driven by the lack of water availability, high levels water demand and the need for reliable sources of water. The first objective of this research investigated the perceptions of wastewater reuse using the university community as a representative subset of southwestern Ontario. This is an important research since public acceptance and trust of consumers in the quality of reclaimed water is considered by many to be the most important factor determining the outcomes of water reclamation projects. Some important finding from the completion of the first objective are the following (confidence level of 95% and a margin of error of 5%):

- Knowledge of domestic water consumption amongst the university community is low, with only 24% of the respondents correctly answered that the average daily domestic water usage by Canadians.
- knowledge of fresh water availability in Canada amongst the university community is high, with 92% of the university community correctly answered this question.
- Knowledge of the urban water cycle amongst the university community is low to moderate. Eighty point three percent (80.3%) of the university community knows that wastewater in London is treated by the municipal sewage treatment system, 50% of the university community knows where London’s drinking water comes from and only 26.9 % knows where wastewater is released after treatment.
- University faculty and graduate students are more familiar with the terms “potable water” and “non-potable water” than students and staff.
- Overall water knowledge of the university community regarding water resources and the urban water cycle in London, ON was medium for 60.4%, high for 13.8 % and low for 25.8 % of the respondents.
- Acceptability of reclaimed wastewater for applications not involving drinking or close personal contact was very high (>85%) in all the stated cases, regardless of water availability. Acceptability of applications involving drinking or close personal contact

showed higher variability depending on the respondent's perceived risk. However, when extreme drought conditions are considered, acceptability of applications involving drinking or close personal contact substantially increase.

- Results also show that there is a moderate (0.303) positive relationship between "water knowledge" and "close contact acceptability".
- Regarding trust in terms of the safety of reclaimed water. Results show that the university community has a high degree of trust in qualified university professors and the regional health units, moderate level of trust on government institutions, private consultants and staff at the water treatment facility, and low degree of trust on information coming from the media and the internet.
- Acceptability of reclaimed wastewater increases substantially when the source of reclaimed water is perceived as cleaner than municipal wastewater, such as storm water and greywater. Additionally, acceptability of reclaimed wastewater increased when it is put back into natural systems before use. The highest increase of acceptability was observed when treated wastewater is allowed to percolate into an aquifer (27%), followed by lake augmentation (15.3%) and discharge into a river (11.4%).
- The majority of the university community (90.9 %) would support water reclamation initiatives if the benefits to the environment are extensive and it is safe for humans. Additionally, around 60 % of the university community agrees that there is much scientific/technological uncertainty regarding the removal of chemicals such as pharmaceuticals from reclaimed water and the long-term effects on human health from exposure to these contaminants are not known. This highlights the importance of this type of research at post-secondary institutions.

The second objective of this research was to investigate the suitability and sustainability of a laboratory scale SAT system with secondary effluents and simulated CSO taking into consideration the predominant soils types and local wastewater effluents of southwestern Ontario. Main findings from the second objective are:

- Dissolved oxygen consumption during the wetting cycle is proportional to the hydraulic retention time for experiments with secondary effluent. 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 was also observed 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.
- Low DOC removals from secondary effluents are explained by the high hydraulic conductivity of high permeability soils and the nature of organic carbon in secondary effluents. Removal of DOC from secondary effluents showed dependency on both retention time and column depth up to approximately 50 cm. Correlations are observed between % DO consumption and % DOC reduction shows DOC removal due to biodegradation and adsorption for the first 30 cm of the column and predominantly adsorption between 50 to 90 cm depth. In experiment C, organic matter is also consumed for heterotrophic denitrification.

- *E.coli* from secondary effluents was not detected at the 90 cm depth at all hydraulic retention times and most of the removal occurs during the first 50 cm of the soil column. At least a log 3 removal is achieved by the SAT system. Likewise, total coliforms were almost completed removed from secondary effluents at the 90 cm depth at experiments A (> log 3), B (log 1.7) and C (log 2.1).

- Nitrate removal from secondary effluents by SAT was slightly achieved at the longest retention time of 13.9 hours with an average 15.17 % reduction the 90 cm depth. Although oxygen is not completed consumed in the column effluent, heterotrophic denitrification can be explained by the formation of anaerobic zones in the soil due to the nature and complexity of porous media. After a 15.17% removal, nitrate concentration is still higher than the accepted limit of the Ontario Drinking Water Standards, Objectives and Guidelines.

- DO reduction from CSOs occurs during the first 30 cm of the soil column, which is attributed to higher biological activity of heterotrophic bacteria in the aerobic zone of the column. Unlike the experiments with secondary effluent, an average reduction of surface permeability by 31% was observed after 7 days of wetting.

- The majority of BOD_5 removal occurs during the first 30 cm of the column and reaches a maximum of 54.26 % at the 90 cm depth. Mechanisms of organic matter from CSOs by SAT is a combination of biodegradation, filtration and adsorption processes. A positive correlation is observed between % DO consumption and % BOD_5 reduction for most of the curve which shows that BOD_5 reduction occurs in part due to aerobic biological activity. The high BOD_5 removal in comparison with DO reduction, suggests that there is a large contribution of filtration and adsorption in the removal of particulate and dissolve organic matter in the simulated CSOs..
- Removal of *E.coli* and total coliform concentrations from CSOs were low with a maximum average reduction of log 0.2 and log 0.4 respectively at the 90 cm depth. Total nitrogen removal from simulated CSOs was moderate (42.9 %) and mainly due to nitrification and adsorption. Ammonia is consumed by a combination volatilization and adsorption with subsequent nitrification during the drying cycle.

- Methanol and glucose addition to secondary effluents showed that denitrification greatly improved when available organic matter is provided. 100 % and 88.53 % removals of Nitrate were achieved at a ratio of 6:1 for methanol and glucose respectively. This is consistent with previous studies and provides scientific support for the importance of protecting recharge wetlands for groundwater quality protection in southwestern Ontario since they can provide additional organic matter needed for denitrification.

SAT as an alternative for sustainable water resource management may be feasible in southwestern Ontario in terms of acceptability and the ability of high permeability soils to polish secondary effluents in terms of DOC, *E. coli* and total coliforms. However, issues with the persistence of nitrates affects its suitability for potable aquifer recharge. Therefore, polished secondary effluent from the APCP by SAT will be more suitable for non-potable groundwater recharge. Recharge of potable aquifers may also be a possibility if wastewater effluents are de-nitrified. Even though the removal of E.coli and total coliforms from secondary effluents were very high, disinfection is still recommended for the inactivation of viruses and protozoa.

Regarding 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.

Future research of SAT system in southwestern Ontario should fully characterize DOC to determine the contribution of different compounds such as natural organic matter, SMP, disinfection byproducts and emergent contaminants. It is also important to determine the fractionation of organic carbon removal due to biodegradation, filtration and adsorption. The effects of dilution and storage in the groundwater aquifer should be taken into consideration. Microbiological analysis of de-nitrifying bacteria in the column should be further investigated. Furthermore, it is important to determine column re-aeration rates during the drying period and oxygen transfer from the soil to the wastewater.

Appendices

Appendix 1: US Water reclamation regulations for selected potable and non-potable applications. Source: Asano et al., 2007

	Fodder Crop Irrigation		Process Food Crop Irrigation	
State	Quality Limits	Treatment Required	Quality Limits	Treatment Required
Arizona	1,000 fecal coli/100 mL	Secondary	Not Covered	Not Covered
Florida	200 fecal coli/100 mL 20 mg/L CBOD 20 mg/L TSS	Secondary Disinfection	No detectable fecal coli/100 mL 20 mg/L CBOD 5 mg/L TSS	Secondary Filtration Disinfection
California	Not specified	Oxidation	Not specified	Oxidation
Texas	200 fecal coli/100 mL 20 mg/L BOD 15 mg/L CBOD	Not specified	200 fecal coli/100 mL 20 mg/L BOD 15 mg/L CBOD	Not specified

	Food Crop Irrigation		Recreational Impoundments	
State	Quality Limits	Treatment Required	Quality Limits	Treatment Required
Arizona	No detectable fecal coli/100 mL 2 NTU	Secondary Filtration Disinfection	No detectable fecal coli/100 mL 2 NTU	Secondary Filtration Disinfection
Florida	Use prohibited	Use prohibited	No detectable fecal coli/100 mL 20 mg/L CBOD 5 mg/L TSS	Secondary Filtration Disinfection
California	2.2 total coli/100 mL	Oxidation	2.2 total coli/100 mL	Oxidation

	2 NTU	Coagulation Filtration Disinfection		Disinfection
Texas	Use prohibited	Use prohibited	20 fecal coli/100 mL 5 mg/L BOD or CBOD 3 NTU	Not specified

Appendix 2: British Columbia municipal sewage regulation. Source: CMHC, 2005

Class	Application	Effluent Quality Requirements				
		CFU/ 100 mL	BOD (mg/L)	TSS (mg/L)	pH	Turb (NTU)
Unrestricted Public Access	Urban Parks, Playgrounds Cemeteries Golf Courses School grounds Landscaping Vehicle washing Toilet flushing Fire protection Agricultural Aquaculture, food crops Orchards and vineyards Pastures Seed crops	< 2.2	< 10	< 5	6 to 9	<2
Restricted Access	Recreational Stream augmentation Snow making (not for sports)	< 200	< 45	< 45	6 to 9	-

	Landscape waterfalls Boating and fishing					
Monitoring		Daily	Weekly	Daily	Weekly	Continuous

Appendix 3 : Reclaimed water quality criteria for Alberta, Saskatchewan, Manitoba and Prince Edward Island. Source: CMHC, 2005

Application	Effluent Quality Requirements				
	CFU/ 100 mL	BOD (mg/L)	TSS (mg/L)	Total P (mg/L)	Total N (mg/L)
	Alberta				
Non-food and golf course irrigation	< 200	<100	<100		
	Saskatchewan				
Agircultural non-food	< 1000				
Agricultural food	< 2.2				
Golf course irrigation	< 200				
	Manitoba				
Golf course / landscape irrigation	< 200				
	Prince Eduard Island				
Golf course irrigation	< 2.2	<10	<10	<5	<5

Appendix 4. Typical range of effluent quality after secondary treatment

Source: Asano et al., 2007

Const	Unit	Untreated wastewater	Conventional AS	AS with BNR	Membrane Bioreactor
TSS	mg/L	120 - 400	5 - 25	5 - 20	< 1
BOD	mg/L	110 - 350	5 - 25	5 - 15	< 1 - 5
COD	mg/L	250 - 800	40 - 80	20 - 40	< 10 - 30
TOC	mg/L	80 - 260	10 - 40	8 - 20	0.5 - 5
Total N	mg N/L	20 - 70	15 - 35	3 - 8	<10 $^{\text{with BNR}}$
Total P	mg P/L	4 - 12	4 - 10	1 - 2	0.5-2 $^{\text{with BNR}}$
Turbidity	NTU		2 -15	2 -8	<1
Metals	mg/L	1.5 - 2.5	1 - 1.5	1 - 1.5	trace
Surfact.	mg/L	4 - 10	0.5 - 2	0.1 - 1	0.1 - 0.5
TDS	mg/L	270 - 860	500 - 700	500-700	500-700
Total Coliform	No/100 mL	10^6 - 10^9	10^4 - 10^5	10^4 - 10^5	< 100
Protozoa	No/100 mL	10^1 - 10^4	10^1 - 10^2	0 - 10	0 - 1
Viruses	PFU/100 mL	10^1 - 10^4	10^1 - 10^3	10^1 - 10^3	1 - 10^3

Curriculum Vitae

Name: DIEGO VELASQUEZ

Post-secondary Education and Degrees:

The University of Western Ontario
London, Ontario
PhD Candidate – Civil and Environmental Engineering - 2010-2016

The University of Western Ontario
London, Ontario, Canada
Masters of Environment and sustainability - 2008

University EAFIT
Medellin, Colombia
BESc – Mechanical Engineering - 2002.

Related Work Experience

ETT - Oct 2014 - Present
Sewer Asset Planning
Water Infrastructure Management
Toronto Water, City of Toronto

Technical Trainee Internship - Sept 2013 – March 2014
Sewer Asset Planning
Water Infrastructure Management
Toronto Water, City of Toronto

Workshop Instructor – 2009 - 2014
Environmental Life Cycle Assessment
Centre for Environment & Sustainability
Western University, London, Ontario

Teaching Assistant – 2010- 2014
Civil and Environmental Engineering
Western University, London, Ontario

Research Associate – Sep 2008 – Jan 2010
Catchment Research Facility (CRF)
Western University, London, Ontario

Environmental Research Internship - May 2008 – Aug 2008
Trojan Technologies
London, Ontario

Awards:

R.M. Quigley Award – Geotechnical Research Centre – UWO 2014

Workshop Award – The Canadian Water Network - 2014

International Internship Award - Students for Development Program, Association of Universities and Colleges of Canada (AUCC) - 2009

Workshop Award - Community of practice on ecosystem approaches to health (CoPHEH – Canada) - 2009

Workshops Attended:

Paddling together: Integrated Traditional and Western Water Knowledge
Canadian Water Network
North Bay, ON
2014

Multidisciplinary Perspectives of Sustainability Workshop
Richard Ivey School of Business
Western University, London, Ontario
2012

Drinking Water Treatment Technologies - Hands on training
Walkerton Clean Water Centre, Ontario
2010

Ecosystem Approaches to Health Training Program
Community of practice on ecosystem approaches to health (CoPHEH – Canada)
University of Guelph, Guelph, Ontario
2009

Publications:

Velasquez D., Yanful E., Sun W. Soil Aquifer Treatment of Secondary Effluents and CSOs in Southwestern Ontario. Conference Proceedings. 14th International Environmental Specialty Conference. CSCE Annual Conference, London, ON, Canada, 2016.

Velasquez D. and Yanful E. Water reuse perceptions of students, faculty and staff at Western University, Canada. 2015. IWA Publishing. Journal of Water Reuse and Desalination. 05.3. 2015.

M. Bittencourt, E. K. Yanful, **D. Velasquez** and A. E. Jungles. Post Occupancy Life Cycle Analysis of a Green Building Energy Consumption at the University of Western Ontario in London – Canada. World Academy of Science, Engineering and Technology, 67, 2012.