

Identification and Treatment of Critical Contaminants for Managed Aquifer Recharge (MAR) with Reclaimed Water

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Residential and employment growth places great pressure on well-based potable water supply and stream-based wastewater treatment systems, which are common in many areas of Canada. To ensure that increased potable water demands and associated increases in wastewater discharges can be met, sustainable water management strategies are needed. One water reuse application, managed aquifer recharge (MAR) with reclaimed water, has been recognized as a potential strategy for indirect potable reuse. However, MAR systems are quite complex and contain a lot of uncertainties. In particular, an investigation of contaminant removal to achieve water quality levels suitable for MAR is needed. To determine water quality limits for MAR with reclaimed water, current water reuse regulations or guidelines which specify MAR requirements and worldwide MAR case studies were first reviewed. The critical contaminants for MAR with reclaimed water were then identified based on wastewater treatment plant (WWTP) effluent monitoring data from a case study and literature data. Water treatment technologies to remove these identified critical contaminants were finally evaluated and the feasible treatment train was recommended for the pre-treatment of MAR with reclaimed water.

The establishment of a MAR system depends on the source of recharge water, the selection of a recharge method and site, the type of water treatment systems, and the ultimate purpose of recovered water. Various components of a MAR system are closely related and integrated. At present, detailed regulations or guidelines to guide MAR with reclaimed water are unavailable in most countries. However, a regulatory framework can be proposed through a review of the currently available regulations/guidelines. Various existing MAR projects in many countries such as USA, Australia, Belgium, Israel, and China can be analyzed in the context of this framework and used as a reference for the implementation of future MAR systems.

The identification of critical contaminants for MAR with reclaimed water is important for MAR implementation. However, the lack of MAR regulatory documents in Ontario and contaminant monitoring data increase the difficulties of this task. To solve the problem, a list of recharge water parameter limits for MAR was defined and an approach to select critical contaminants for MAR was developed. Predominant contaminants, which are the residual regulated substances in a wastewater effluent for which concentrations are higher than the defined recharge water limits, were identified

based on WWTP effluent monitoring data from a case study. Potential microbial and organic contaminants, which are included in the defined regulated contaminants list and have high possibility to exist in the effluent, were selected based on the occurrences and concentrations of regulated contaminants in wastewater effluents from the literature. Potential emerging contaminants, which are not regulated but may be important for MAR with reclaimed water, were also chosen according to their consumption volumes, bioaccumulation, ecological and health effects, and occurrences in wastewater effluent from published studies. Finally, a list of critical contaminants for MAR with reclaimed water, which comprise these three types of contaminants, was determined.

An adequate water pre-treatment system is needed for MAR with reclaimed water to remove a wide range of residual chemical and microbial contaminants in wastewater effluents. Different types of water treatment technologies, including conventional wastewater treatment, conventional drinking water treatment, and advanced processes including membrane filtration and oxidation processes, can be helpful to remove critical contaminants for MAR with reclaimed water. Based on the identified types of critical contaminants, different treatment alternatives were proposed and evaluated based on previous studies available in the literature. Through the combination of different treatment units, potential treatment trains were proposed. Based on this initial assessment, the most cost-effective treatment train of ultrafiltration, reverse osmosis, UV-based advanced oxidation processes (AOPs) for the pre-treatment of MAR with reclaimed water was proposed. This treatment scenario was compared with the normal treatment trains in previous MAR case studies for potable reuse. It was found that this treatment is more robust but may be more expensive.

Overall results of this work established methods to evaluate MAR pre-treatment strategies that can be used by municipalities that are planning MAR with reclaimed water. As well, this research can be applied to assess the feasibility of MAR, but will need to be taken together with other aspects (recharge sites, recharge methods, recharge facilities) to assess overall applicability of the work.

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List of Abbreviations

AOPs: Advanced Oxidation Processes

ASR: Aquifer Storage and Recovery

ASTR: Aquifer Storage, Transfer and Recovery

BOD: Biochemical Oxygen Demand

CBOD: Carbonaceous Biochemical Oxygen Demand

COD: Chemical Oxygen Demand

CTC: Carbon Tetrachloride

CVC: Credit Valley Conservation

DALYs: Disability Adjusted Life Years

DEHP: Di(2-ethylhexyl)phthalate

DO: Dissolved Oxygen

FAT: Full Advanced Treatment

GAC: Granular Activated Carbon

GWRS: Groundwater Replenishment System

LSI: Langelier Saturation Index

MAR: Managed Aquifer Recharge

MF: Microfiltration

MFGRP: Montebello Forebay Groundwater Recharge Project

MFI: Membrane Fouling Index

MNR: Ministry of Natural Resources

MOE: Ministry of Environment

MWR: Ministry of Water Resources

NDMA: N-nitrosodimethylamine

NF: Nanofiltration

NRMMC-EPHC-NHMRC: National Resource Management Ministerial Council, Environment Protection and Heritage Council, and National Health and Medical Research Council

NTA: Nitrilotriacetic Acid

PAC: Powdered Activated Carbon
PAHs: Polycyclic Aromatic Hydrocarbons
PFCs: Perfluorochemicals
PFOA: Perfluorooctanoate
PFOS: Perfluorooctane Sulfonate
PWQO: Provincial Water Quality Objectives
QMRA: Quantitative Microbial Risk Assessment
RO: Reverse Osmosis
SAT: Soil Aquifer Treatments
SDI: Silt Density Index
SGF: Slow Granular Filtration
SRT: Solid Retention Time
SS: Suspended Solids
TDS: Total Dissolved Solids
TOC: Total Organic Carbon
TOX: Total Organic Halogen
TSS: Total Suspended Solids
UF: Ultrafiltration
U.S.EPA: United States Environmental Protection Agency
UV: Ultraviolet
WCED: World Commission on Environment and Development
WHO: World Health Organization
WWTP: Wastewater Treatment Plant

Chapter 1

Introduction and Approach

1.1 Introduction

Many areas in Canada rely on well-based potable water supply and stream-based wastewater treatment systems, and this is also true for many regions in southern Ontario, Canada. However, residential and employment growth is placing great pressure on these systems. For this reason, there is a need to conduct long-term planning to assess water and wastewater options that will ensure sustainable development for the community. Halton Region is located in an area of rapid population growth in southern Ontario, and as such they are assessing future options for water and wastewater planning. MAR with reclaimed water has been recognized as a potential strategy to provide an alternative water source for indirect potable reuse in this area. However, the lack of MAR regulatory documents in Ontario increases the difficulties in assessing this option. Therefore, this study was done in collaboration with Halton Region to investigate the feasibility of MAR, in order to provide information that can be compared with other water supply options.

Based on the provincial Growth Plan (Ontario Ministry of Infrastructure, 2006) and the Halton Region Official Plan (The Regional Municipality of Halton, 2009), the residential population in Halton is expected to grow from 493,045 in 2011 to 752,537 in 2031, and the serviced employment (employees) population will increase from 250,932 in 2011 to 390,000 in 2031 (The Regional Municipality of Halton, 2011a). Water capacity calculations conducted by the Halton municipal planning and works committee have determined that some areas in the Region have no unallocated capacity to support future developments (The Regional Municipality of Halton, 2007b). To ensure that the increased potable water demands and associated increase in wastewater discharges can be met, the Halton Water and Wastewater Master Plan (The Regional Municipality of Halton, 2011a) proposed expansion of existing well fields and upgrades to existing water and wastewater infrastructure. However, pumping water from regional aquifers and discharging sewage to the stream is not a sustainable strategy since water is continuously taken from the groundwater system but not returned to its source. This practice may cause the groundwater level decline, and also challenge wastewater treatment and discharge limits. To provide a reliable alternative water source and reduce

the discharge of wastewater from the municipal wastewater treatment plant (WWTP), a sustainable water management strategy is needed.

Managed aquifer recharge (MAR) with reclaimed water is a purposeful recharge of reclaimed water to aquifers for recovery and reuse (Dillon *et al.*, 2009). Due to its sustainability, MAR is being studied as a potential strategy for indirect potable reuse. However, MAR systems are quite complex and contain a lot of uncertainties. In particular, an investigation of reclaimed water pre-treatment technologies to achieve water quality levels suitable for MAR is needed. This can be used to assess the complexity and costs of an MAR system and will help to assess if this approach is a feasible alternative for future planning.

1.2 Objectives

To investigate MAR with reclaimed water, three major goals were determined for this research:

1. Analyze currently available worldwide water reuse regulations/guidelines and MAR with reclaimed water case studies to define the recharge water quality limits for indirect potable reuse.
2. Identify the critical contaminants in wastewater effluents that will require further treatment for MAR with reclaimed water.
3. Select water pre-treatment options that can remove the identified critical contaminants.

The specific objectives of the first goal as follows:

- Analyze the water reuse regulations/guidelines which specify requirements for MAR with reclaimed water and propose a regulatory framework.
- Critically analyze worldwide MAR with reclaimed water case studies to learn from their planning, designing, and management experience.
- Determine the typical reclaimed water quality parameter limits for MAR based on worldwide water reuse regulations/guidelines.

The specific objectives of the second goal are as follows:

- Define the maximum limits for microbial and chemical parameters based on Ontario and Health Canada drinking water standards, Ontario Provincial Water Quality Objectives

(PWQO), and California, Florida, Idaho water reuse regulations.

- Identify the critical predominant contaminants in wastewater effluents, for which concentrations are higher than the defined water quality targets.
- Identify potential additional microbial and organic contaminants that are regulated and can be present in wastewater effluents, but are not routinely monitored in wastewater effluents.
- Identify potential emerging contaminants that are not regulated, but may be prevalent in wastewater effluents and important for indirect potable reuse.

The specific tasks to achieve the third goal are as follows:

- Propose treatment options according to the types of critical contaminants identified.
- Evaluate the removal efficiency of the proposed treatment options for critical contaminant removal based on data available in the published literature.
- Select feasible potential treatment alternatives based on defined target removal efficiencies and assigned treatment efficiency credits.
- Evaluate overall removal efficiencies of the critical contaminants by two selected treatment trains, and conduct a preliminary cost evaluation.

1.3 Thesis Structure

Chapter 2 introduces MAR and discusses current worldwide water reuse regulations and guidelines which set the requirements for MAR. A regulatory framework based on the current regulation/guidelines is proposed. Finally, an analysis of case studies that used MAR with reclaimed water is also provided and discussed within the context of the proposed regulatory framework.

Chapter 3 provides a characterization of the case study area in the Region of Halton. This chapter also provides details on Halton water and wastewater systems, including future plans for these systems to accommodate growth in the study area.

Chapter 4 focuses on selecting the critical contaminants for MAR with reclaimed water. Due to the lack of water reuse regulatory documents in Ontario, the water quality targets for recharge water are defined based on the current Health Canada and Ontario drinking water standards, Ontario

Provincial Water Quality Objectives and worldwide water reuse regulations/guidelines. Critical contaminants include are predominant contaminants, potential additional microbial and organic contaminants, and potential emerging contaminants. The predominant contaminants in wastewater effluent were identified by statistical analysis of WWTP case study data. Potential organic contaminants, which are included in the drinking water or water reuse regulations but not regulated or monitored in WWTP effluents were also identified and values were determined based on literature data. In addition, potential emerging contaminants, which are not regulated but may be important for indirect potable reuse, were similarly selected and evaluated based on data in wastewater effluents in published studies.

Chapter 5 provides a list of promising water reclamation technologies to remove each type of critical contaminant. The efficiency of each technology for the removal of selected critical contaminants was studied, and water treatment efficiency credits for each contaminant were assigned based on literature data. The concept of target removal efficiency was defined, which is calculated using the maximum concentration and the water quality limit of each contaminant. The individual water treatment units, which can exceed target removal efficiencies, were selected and combined to form alternative water treatment trains. An overall treatment efficiency evaluation and a preliminary cost evaluation of alternative water treatment trains were then conducted.

Chapter 6 presents conclusions and recommendations of this research.

Chapter 2

Water Reuse through MAR: Learning from Regulations/Guidelines and Case Studies

This chapter is being prepared as a manuscript for the submission to a scientific journal (e.g. Water Research).

2.1 Introduction

Various places around the world are currently or potentially experiencing the problem of water shortage due to rapid population growth, water contamination, groundwater exhaustion, and unbalanced allocation of water resources caused by geographical and seasonal variations (Asano and Cotruvo, 2004; Chen *et al.*, 2012). For this reason, an emerging paradigm of sustainable water resources management is developing. Some strategies, including water conservation and water reclamation and reuse, aim to ensure that current water demands are met without compromising future needs (WCED, 1987; Asano *et al.*, 2007).

Water reclamation and reuse is an integrated process in which different water treatment technologies are used to treat wastewater. The reclaimed water may be used for irrigation, urban uses, industrial uses, and supplementing water resources (Anderson, 2003). This practice is a promising water resources management option since the recycling of wastewater can not only provide a reliable alternative water source but also reduce the environmental pollution caused by the discharge of wastewater.

One water reuse application, Managed Aquifer Recharge (MAR) with reclaimed water (Figure 2.1), is an intentional process of recharging water into aquifers for further recovery or environment uses (Dillon *et al.*, 2010; Ward and Dillon, 2012). Unlike the natural aquifer recharge process in which aquifers are replenished by rain penetrating soil, or streams infiltrating their banks, MAR is an artificial means to replenish groundwater. MAR's advantages are numerous, including providing additional natural treatments to enhance water quality, replenishing groundwater basin to mitigate subsidence, increasing water supplies and preventing salt water or sea water intrusion, storing water underground to buffer seasonal supply and demand variations and reduce water

evaporation, maintaining groundwater-dependent ecosystems, mitigating floods and flood damage, and facilitating the improvement of urban landscape (Dillon *et al.*, 2009; Hochstrat *et al.*, 2010; Kazner *et al.*, 2012; U.S.EPA, 2012a).

However, implementing a MAR system is quite challenging since multiple factors in aspects of urban planning, stormwater management, wastewater management, and water supply should be taken into consideration (Dillon *et al.*, 2009b). In addition, the lack of a mature regulatory framework for MAR system planning also increases the difficulties of MAR establishment (Asano and Cotruvo, 2004; Hochstrat *et al.*, 2010).

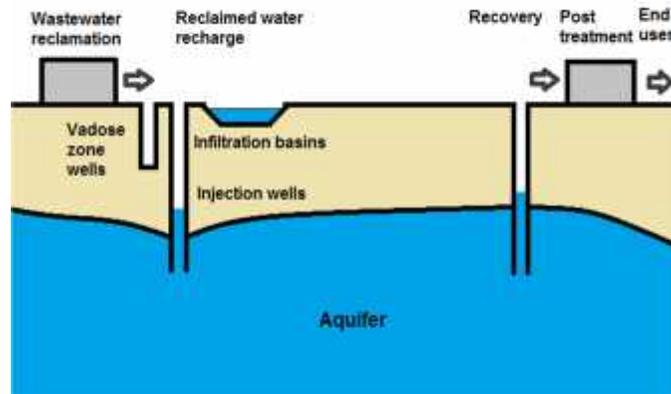


Figure 2.1 Schematic Managed Aquifer Recharge with Reclaimed Water

Due to the wide range of technical and regulatory challenges, current research for MAR is being conducted in various areas. Some studies focus on the specific MAR cases, such as investigating the removal of pathogenic or chemical contaminants during managed aquifer recharge processes (Levantesi *et al.*, 2010; Patterson *et al.*, 2010; Pitoi *et al.*, 2011; Sidhu and Toze, 2012), selecting appropriate recharge locations (Daher *et al.*, 2011; Rahman *et al.*, 2012; Rahman *et al.*, 2013), and exploring MAR design and operation issues (Maliva *et al.*, 2009; Cockett and Pidlisecky, 2014). Other studies are investigating MAR from a general perspective, by addressing political or legal considerations for MAR (Asano and Cotruvo, 2004; Hochstrat *et al.*, 2010; Ward and Dillon, 2012), management of MAR (Bouwer, 1996; Dillon, 2005), and economics of MAR (Dillon *et al.*, 2010). However, few studies illustrate a general regulatory framework of MAR through analyzing or

comparing specific MAR cases. Therefore, the objectives of this review are to critically summarize and compare worldwide water reuse guidelines or regulations for MAR with reclaimed water, create a regulatory framework based on current guidelines or regulations, and to analyze different MAR case studies that use reclaimed water in the context of this framework. To provide background knowledge of MAR, this review also presents MAR principles.

2.1.1 MAR Types

The existing MAR systems can be classified into ten different types (Figure 2.2), modified from the categories illustrated in the Australian Water Reuse Guidelines for MAR (NRMMC-EPHC-NHMRC, 2009a).

Aquifer Storage and Recovery (ASR)

ASR is the underground storage of water through injecting and recovering from the same well (Pyne, 1995). This type of MAR is a cost-effective water storage option with a small surface footprint (Maliva *et al.*, 2006).

Aquifer Storage, Transfer and Recovery (ASTR)

ASTR refers to injecting and recovering water from separate wells. This method is an upgraded version of ASR and is quite effective to improve stored water quality due to the longer residence time (Maliva and Missimer, 2010).

Vadose Zone Wells

Vadose zone wells, also called “dry wells”, are shallow wells where groundwater is deep. Their common uses are infiltration and disposal of storm runoff where rainfall is low and no storm sewers or combined sewers are available (Bouwer, 1996).

Percolation Tanks and Recharge Weirs

Percolation tanks and recharge weirs are dams constructed in transient streams to retain stormwater that can then penetrate through the stream bed to increase the storage in unconfined aquifers (NRMMC-EPHC-NHMRC, 2009a).

Rainwater Harvesting

In rainwater harvesting, rainwater is collected and redirected to a deep pit with percolation. This process is efficient to augment the natural filtration of rainwater to underground formations, and is beneficial to restore the hydrological cycle in urban areas (Kim *et al.*, 2012).

Bank Filtration

Bank filtration is a way to induce infiltration from a surface water body by extracting groundwater from a well or caisson near or under a river or lake (NRC, 2008). In this type of MAR, the natural treatment process can improve the quality of surface water in an inexpensive and sustainable way and the high quality surface water can replenish the groundwater (Tufenkji *et al.*, 2002).

Infiltration Galleries

Infiltration galleries are percolation trenches in which a permeable medium has internal void spaces to facilitate infiltration (Bekele *et al.*, 2013). They are among the oldest known ways of harvesting clean water (Kresic, 2007).

Dune Filtration

In dune filtration, water is recharged into ponds built in dunes and later extracted from wells or ponds at lower elevation. This process is mainly used for the improvement of water quality and to balance supply and demand (NRMMC-EPHC-NHMRC, 2009a).

Infiltration Ponds

Infiltration ponds are large open water ponds which are either excavated or located in a place surrounded by a bank. This practice has excellent pollutant-removal efficiency and is considered to be an effective means to recharge groundwater and increase base flow to stream systems (U.S. EPA, 2012b).

Recharge Releases

In this type of MAR, dams are built on ephemeral streams to detain flood water. Therefore, the release rate of water downstream can be slowed so that water can be directly recharged into underlying aquifers (NRMMC-EPHC-NHMRC, 2009a).

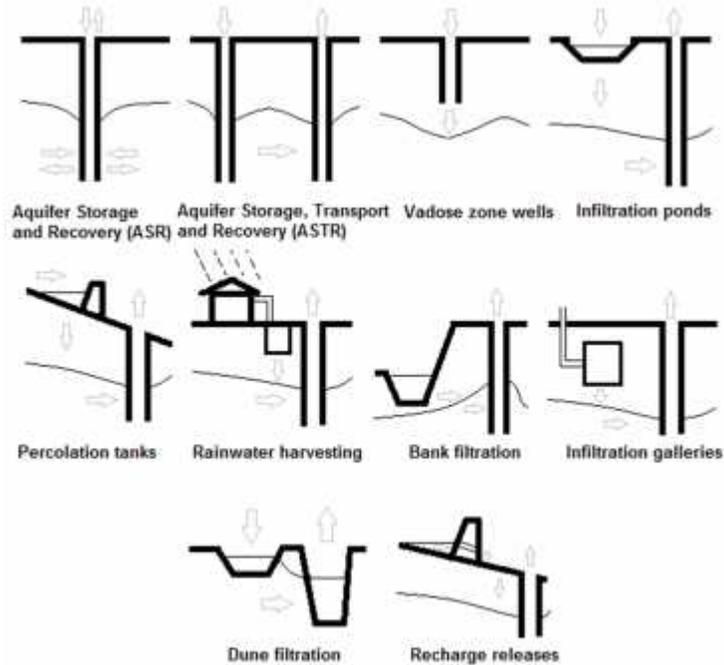


Figure 2.2 Schematics Showing Various Types of MAR

2.1.2 MAR Components

According to the U.S.EPA 2012 Water Reuse Guidelines (U.S.EPA, 2012a), MAR systems can be described as including five elements: sources of recharge water, recharge methods, sub-surface storage, recovery of water, and ultimate uses of recovered water. However, since sub-surface storage and recovery of water are abstract terms, they cannot be clearly determined during the implementation of MAR systems. Two new terms, recharge sites and water treatments, are more useful and should be considered for MAR establishment. Therefore, sources of recharge water, recharge methods, recharge sites, water treatment, and ultimate uses of recovered water should be considered as the new key factors that are required for MAR systems.

In terms of recharge water, aquifers can be recharged from different sources, including stormwater, reclaimed wastewater from wastewater treatment plants, surface water from rivers or lakes, groundwater drawn from other aquifers or drawn remotely from the same aquifer, or drinking water from potable water distribution systems (NRMMC-EPHC-NHMRC, 2009a). The type of recharge water will depend not only on availability and quality, and may also be influenced by the ultimate use of the groundwater.

Two recharge methods used for MAR are direct injection and surface spreading. Selecting a recharge method depends on many factors such as aquifer type, aquifer depth, land availability, groundwater quality, and costs. Figure 2.3 shows a typical procedure for selecting a suitable aquifer recharge method (U.S. EPA, 2012a), where several levels of criteria have been taken into consideration. The first criterion is aquifer type. If the aquifer is confined, direct injection should be chosen. Otherwise, the second criterion (groundwater depth) should be considered. For unconfined aquifers, the cost of direct injection wells will be higher when the depth to groundwater increases. Therefore, a critical value of groundwater depth, which usually ranges from 100 to 201 m, should be determined for each situation. If the depth of groundwater is less than the critical value, direct injection is preferable. If not, the third criterion (land availability) should be considered. If cost-effective land is available at the appropriate place, surface spreading basins can be chosen. If not, vadose zone injection wells are more suitable. Besides these three key factors, other factors such as groundwater quality, ultimate uses, and environmental impacts on neighboring areas should also be taken into account.

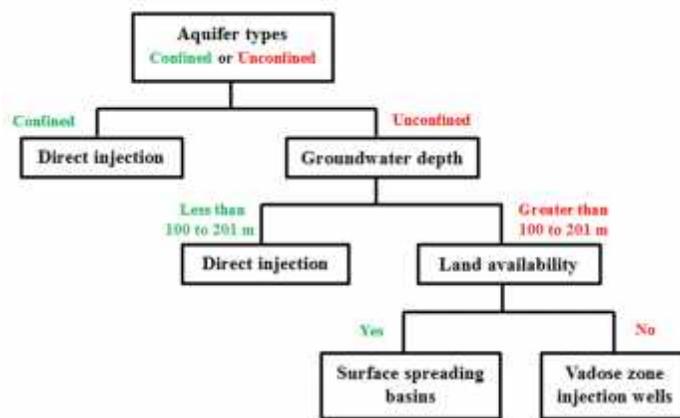


Figure 2.3 Decision Tree for the Selection of Recharge Method

The recharge site will have a great impact on the performance of MAR systems since this element has a close relationship with sub-surface storage and water recovery. For example, sub-surface storage is determined by types and volumes of aquifers, and water recovery is to some extent influenced by the natural treatment processes. Once the recharge location is chosen, the sub-surface characteristics are identified so that storage capacity and hydrogeological purification can be determined. The selection of recharge sites is a complex decision-making process. Different levels of factors including geological and hydrogeological characteristics, social and economic policies, natural conservation, and environmental impacts should be considered (Rahman *et al.*, 2012).

Water treatments in MAR systems comprise both artificial and natural processes. For the former, different engineered technologies are combined to pre-treat recharge water or post-treat recovered water in order to remove specific contaminants or constituents and thus, achieve the required water quality (Dillon *et al.*, 2008). Underground natural purification is considered to remove some microbial and chemical contaminants, mainly through adsorption or biodegradation (Schmidt *et al.*, 2007; Maeng *et al.*, 2011).

The ultimate uses of water recovered from aquifers vary. Normally, water is reused to secure and enhance the water supply for specific purposes such as drinking, agriculture, industry, and environment. Other uses include barriers against aquifer salinization, flood mitigation, and coastal water quality improvement through the reduction of urban discharge (Dillon *et al.*, 2009).

2.1.3 Essential Considerations for MAR Implementation

Water quality is essential in MAR systems since it greatly influences the choice of water treatment technologies, MAR site selection, and MAR system design and operation. When the final uses of recovered water from aquifers are identified, the required water quality targets can be defined. Even though the underground natural system can provide some treatment of the recharge water, soil aquifer treatment (SAT) is quite complex and not easily controlled (Dillon *et al.*, 2008). Hence, given that the treatment performance of SAT cannot be predicted, different engineered treatment processes should be used to pre-treat or post-treat the recharge water to guarantee the required quality of recovered water is achieved. The selection of water treatment units or trains is usually based on the quality of

recharge water. As an example, if nitrogen is identified as a critical constituent whose concentration is significantly higher than the specified value, de-nitrification should be considered.

The subsurface characteristics of MAR sites also have a close relationship with water quality. During underground geochemical processes, different physicochemical and biological reactions can change the water quality (Essandoh *et al.*, 2011). Reactions such as iron precipitation, biological degradation, oxidation, soil filtration or adsorption can help remove contaminants (Dillon *et al.*, 2008). However, some processes may increase substance concentrations in the water. For example, when water flows along an aquifer, small quantities of sodium chloride in soil dissolve into water, thus increasing the sodium and chloride contents (Fox, 2007). As well, clogging may occur due to the quality of recharge water. Typical water quality parameters such as the Langelier saturation index (LSI), silt density index (SDI), and membrane fouling index (MFI) are defined to characterize the potential of recharge water to cause well corrosion or fouling (U.S.EPA, 2012a). For the successful implementation of MAR systems, MAR site hydrogeological and geochemical characteristics should be suitable to maintain or improve the quality of water travelling underground, while also maintaining good condition of the recharge water quality to ensure the successful infiltration or percolation of water within the aquifer matrix.

The design and operation of MAR systems are to some extent impacted by the water quality. Normally, better recharge water quality requires less underground retention time. Therefore, the distance between the locations of discharging water and withdrawing water should be shorter (Bouwer, 1996). Poor recharge water quality is more inclined to clog recharge areas such as infiltration basins or wells. This clogging can lead to reduced infiltration rates. To maximize infiltration, operational strategies such as water pre-treatment, well redevelopment, physical removal of the clogging layer, or the use of infiltration basin wetting/drying cycles may be implemented during the MAR system operation (Bouwer, 2002).

2.2 Guidelines and Regulations for Water Reuse

2.2.1 General Information

A number of water reuse guidelines and regulations have been developed by specific countries/regions or international organizations. During the past few years, the World Health Organization (WHO) has produced three editions of guidelines for water reuse (WHO, 2006). In North America, two provinces in Canada (British Columbia and Alberta) have regulatory guidelines for water reuse, while in the USA there are national water reuse guidelines published by the Environmental Protection Agency (EPA), 25 state-specific water reuse regulations, and 16 state-specific water reuse guidelines or design standards (Schaefer *et al.*, 2004; Asono *et al.*, 2007). In Europe, there are no European Union level documents, but five countries including Belgium, Cyprus, France, Italy, Spain and two autonomous regions in Italy (Sicily, Emilia Romagna and Puglia) and in Spain (Andalucía, Balearic IS. and Catalonia), have released their own water reuse standards or regulations (Bixio *et al.*, 2006). In Oceania, Australia has developed comprehensive national water recycling guidelines (NRMMC-EPHC-AHMC, 2006; NRMMC-EPHC-NHMRC, 2008; NRMMC-EPHC-NHMRC, 2009a; NRMMC-EPHC-NHMRC, 2009b). In Asia, water reuse regulations have been established by countries such as China, Singapore, Japan, and Korea, mainly for agriculture, aquaculture, municipal, and industrial water reuse purposes (Jiménez and Asano, 2008). In other places, including South America and Africa, few water reuse guidelines or regulations have been published, and instead most countries are following WHO water reuse guidelines (Jiménez and Asano, 2008; Adewumi *et al.*, 2010).

Among these guidelines and regulations, the most notable and widely used are the WHO, U.S.EPA, and Californian water reuse guidelines/regulations. The latest edition of the *WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater*, published in 2006, not only illustrates the assessment of health risks, health-based targets, and health protection measures in the practice of wastewater reuse in agriculture, but also establishes a framework for assessing the sociocultural, environmental, economic and financial, and policy aspects of water reuse projects (WHO, 2006). The WHO guidelines are generally less stringent than regulations or guidelines in some U.S. states or European countries, but have been broadly adopted all over the world, especially in areas that have no water reuse regulations and no capacity to produce higher quality reclaimed

water (Asano *et al.*, 2007). The *U.S.EPA 2012 Guidelines for Water Reuse* were updated in 2012 by the EPA and the Agency for International Development. This document covers various types of water reuse purposes, water reclamation technologies, water reuse program funding, public involvement, and water reuse regulatory programs or applications in different states of the U.S. and even around the world (U.S. EPA, 2012a). In terms of state-specific regulations, the California Department of Public Health updated *Regulations Related to Recycled Water* in 2009 to clearly define 30 terminologies related to water reuse, and contains requirements of recycled water sources, uses, distribution, treatment, system design and operational considerations, and reliability requirements (California Department of Public Health, 2009). This California Regulation is comprehensive and stringent to establish a high level of public protection (Asano *et al.*, 2007). Therefore, the California regulation has been followed by some developed countries, including European countries and high income African countries (Jiménez and Asano, 2008).

2.2.2 Specific Requirements for MAR with Reclaimed Water

Although many water reuse guidelines or regulations have been established throughout the world, few have specific requirements regarding MAR with reclaimed water. The existing regulations or guidelines mainly contain MAR regulatory considerations from the following aspects: (1) recharge water quality requirements, (2) MAR design, operation and maintenance, and (3) ultimate uses of recovered water.

Regulation in British Columbia (Canada)

British Columbia's *Waste Management Act-Municipal Wastewater Regulation* (British Columbia Ministry of Environment, Lands and Parks, 2012) specifies four classes of municipal effluent for discharging to the ground based on the different levels of wastewater treatment. For each class, the water quality and recharge site characteristics are defined, such as subsurface travel time, unsaturated soil depth, and zone of influence. Additionally, this regulation stipulates the design of drainfields and recharge fields such as infiltration basins, sand mounds and seepage beds. Monitoring requirements are also included in the document.

Regulation in California (USA)

In June 2014, the regulation: *Groundwater Replenishment with Recycled Water* released by the California Department of Public Health was officially effective (California Department of Public Health, 2014). In the regulation, groundwater replenishment for indirect potable reuse via surface application and subsurface application are addressed. A public hearing is required prior to the implementation of an aquifer recharge project, since the ultimate use of recovered water from aquifers is normally drinking water. In addition, the criteria propose a multi-barrier approach to ensure the safety of recovered water. Different kinds of groundwater replenishment controls are illustrated, including water source, artificial and natural treatment, dilution control, monitoring, and operational control. For each control, the requirements are stringent and comprehensive. For example, in the control of pathogenic microorganisms, enteric viruses, *Giardia* cysts, and *Cryptosporidium* oocysts, but not *E.coli* or total coliforms, are considered to be the microbial indicators. This specific microbial requirement will require more sophisticated wastewater reclamation and monitoring methods. Moreover, on-going monitoring will be needed, as well as remediation methods to deal with problems in a timely way so as to achieve microbial reduction targets. The most innovative part of the Californian codes is the concept of reclaimed water dilution, which can reduce the concentration of contaminants in reclaimed water without the need to upgrade the wastewater reclamation processes.

Regulation in Florida (USA)

Chapter 62-610 of the Florida Administrative Code, entitled *Reuse of Reclaimed Water and Land Application*, describes groundwater recharge via rapid infiltration basins or injection wells (Florida Department of Environmental Protection, 1999). For surface spreading, secondary treatment and disinfection are the minimum reapplication treatment requirements for the recharge water. Based on different subsurface characteristics and neighbouring potable water sources, additional levels of reapplication treatment, setback distances (distance between the recharge site and nearby protection zones), and hydraulic loading rates are set. For direct injection, the receiving groundwater quality will set the recharge water quality limits and required pre-treatment levels. For example, when the total dissolved solids (TDS) level in the groundwater is less than 3000 mg/L, wastewater should receive full treatment and disinfection (secondary treatment, filtration, multiple barriers for control of pathogens and organics, disinfection) to meet high water quality requirements. Water quality requirements not only specify typical wastewater quality parameters but also include a surrogate

parameter: total organic halogen (TOX) to measure the amount of halogenated organics that may be toxic to humans (Glaze *et al.*, 1977; Williams, 1984). Pilot testing is also required before the implementation of full-scale projects.

Guidelines in Australia

Australian Guidelines for water recycling: Managed Aquifer Recharge is the one of three modules which comprise Phase 2 of the National Water Reuse Guidelines. This document includes a framework for hazard identification and risk assessment of MAR projects, MAR operational management, as well as monitoring issues (NRMMC-EPHC-NHMRC, 2009a). Since the main purpose of this document is to provide general principles for the implementation of MAR projects, the guideline does not specify recommended water quality parameters, operational factors, or monitoring frequencies. To be applicable for a variety of MAR projects, this document covers different types of source water, aquifers, and reuse purposes. The guidelines' major characteristic is the establishment of a logical, staged process for risk assessment and management in MAR projects. The procedure consists of four stages: 1) collection of the available information and entry-level assessment; 2) risk assessment and preventive measures identification; 3) project construction and residual risk assessment; 4) project operation and verification. Two types of qualitative risk assessment are described in the document: the first is a broad assessment for general projects, and the second is a simplified assessment for specific projects in defined conditions.

Other Guidelines or Regulations

Unlike the guidelines or regulations discussed above, other available water reuse directives either do not include managed aquifer recharge as an end-use option for reclaimed water or specify only general MAR requirements. In the U.S.EPA 2012 Water Reuse Guidelines, groundwater recharge for non-potable uses or indirect potable use are regulated and for each category, reclaimed water quality, monitoring frequency, and setback distances are defined. Idaho's *Recycled Water Rules* indicate that recycled reclaimed water quality should follow the Idaho Ground Water Quality Rule, and the determination of a system's design or operation parameters should be site-specific (Idaho Department of Environmental Quality, 2009). In Pennsylvania, the *Reuse of Treated Wastewater Guidance Manual* specifies that groundwater recharge by directly injecting reuse water requires Class A+ water quality and a minimum retention time 12 months for potable uses, while groundwater recharge by

infiltration basins requires Class A or better and a 9-month retention time for drinking purposes (Pennsylvania Department of Environmental Protection, 2012). Chinese standards of reclaimed water quality set 21 water quality parameter limits for reclaimed water to be used for recharging aquifers (MWR, 2006).

Summary of Reclaimed Water Quality and Treatment Requirements for MAR

The water quality needed for MAR is an important consideration, as treatment and monitoring requirements will play a large role in the design and operation of the system. Therefore, the guidelines or regulations discussed above were surveyed to determine the required quality of the reclaimed water for MAR, and the results of each are summarized in Table 2.1. In terms of microbial limits, it can be seen that most documents include limits for fecal coliforms or total coliforms, but only the latest California regulation specifies the treatment targets for other groups of pathogen indicators including enteric viruses, *Giardia* cysts and *Cryptosporidium* oocysts. As discussed above, Australia uses Quantitative Microbial Risk Assessment (QMRA) to establish acceptable microbial water quality limits. Since the water recovered from aquifers can be used for potable purposes, some inorganic or organic contaminants regulated in drinking water standards have been taken into consideration. In some cases, limits have been set for specific chemical and physical parameters, including those that measure some standard wastewater monitoring parameters (e.g. TSS, BOD, nitrogen). However, in many cases and in particular for inorganic and organic chemicals, the guidelines state that values must meet environmental or drinking water standards. The only regulations to set specific levels for chemical parameters are the California and China regulations.

The treatment and setback requirements for MAR in the various guidelines or regulations were also surveyed and summarized in Table 2.2. Overall results show that different levels of water treatments apply for various categories of MAR with reclaimed water. Secondary treatment is the basic treatment requirement for recharge water. To ensure the quality of recharge water and groundwater, additional treatments such as filtration, disinfection, advanced treatments are also required to treat reclaimed water. Additionally, SAT serves as the extra natural treatment barrier for the removal of contaminants. Therefore, MAR via direct injection requires a higher level of pre-treatment than MAR via surface spreading. The performance of SAT depends on the underground travelling time or distance of water. Normally, the longer travelling time or distance is, the better

water quality can be guaranteed. To ensure the performance of SAT, the setback distances between recharge sites and water withdrawal sites or neighboring sensitive areas such as water bodies are specified in the regulations. The determination of setback distances is normally based on experimental tracer studies or numerical modelling.

Table 2.1 Required Water quality for Managed Aquifer Recharge with Reclaimed Water

Water Reuse Regulations or Guidelines	Categories	Recharge Water Quality Limits
<i>Waste Management Act: Municipal Wastewater Regulation</i> ¹ (British Columbia, Canada)	Infiltration basin for indirect potable use	BOD ₅ <5mg/L, Turbidity≤1 NTU, TSS<5 mg/L, Fecal coliforms: median<1 CFU/100 mL (7 day median) or 2.2 MPN/100 mL (any sample).
<i>Groundwater Replenishment with Recycled Water</i> ² (California, USA)	Surface or Subsurface application for indirect potable use	12-log enteric virus reduction, 10-log <i>Giardia</i> cyst reduction, 10-log <i>Cryptosporidium</i> oocyst reduction Total nitrogen≤10 mg/L (average of two consecutive samples) Total Organic Carbon: TOC≤0.5 mg/L (average) Inorganics: 18 chemicals regulated Radionuclides: 6 chemicals regulated Organic chemicals: 27 volatile organic & 33 non-volatile organic chemicals regulated Disinfection byproducts (DBPs): four types of DBPs (11 chemicals) regulated
<i>Reuse of Reclaimed Water and Land Application</i> ³ (Florida, USA)	Rapid infiltration basins/ Absorption fields	No detectable fecal coliforms/100 mL, NO ₃ ⁻ -N≤12 mg/L, TSS≤5 mg/L (maximum values), Total Nitrogen≤10 mg/L (annual average), Other chemicals must comply with primary and secondary drinking water standards.
	Injection to G-II ground water having TDS <3000 mg/L	No detectable total coliforms/100 mL, TSS≤5 mg/L (maximum value), TOC≤3 mg/L (monthly average) & 5 mg/L (maximum value), TOX<0.2 mg/L, Total Nitrogen<10 mg/L (annual average), Other chemicals must comply with primary and secondary drinking water standards.
	Injection to G-II ground water having TDS >3000 mg/L	No detectable total coliforms/100 mL, TSS<5 mg/L (maximum value), Other chemicals must comply with primary drinking water standards.

(To be continued)

Table 2.1 Required Water Quality for Managed Aquifer Recharge with Reclaimed Water

Water Reuse Regulations or Guidelines	Categories	Recharge Water Quality Limits
<i>Australian Guidelines for water recycling: Managed Aquifer Recharge</i> ⁴ (Australia)	13 types of MAR	Pathogens: <10 ⁻⁶ DALYs (Disability Adjusted Life Years) per person per year, Inorganic/organic chemicals and nitrogen species: must meet the environmental targets for the aquifer, Salinity and sodicity: TDS<500 mg/L, Turbidity and particulates: <1 NTU, No radioactive isotopes.
<i>U.S.EPA 2012 Guidelines for Water Reuse</i> ⁵ (USA)	Groundwater recharge for non-potable uses	Site specific and use dependent
	Groundwater recharge by spreading into potable aquifers	No detectable total coliforms/100 ml, 1 mg/l Cl ₂ residual (minimum values), Turbidity 2 NTU, TOC 2 mg/L, pH = 6.5-8.5, Other chemicals must meet drinking water standards after percolation through vadose zone.
	Groundwater recharge by injection into potable aquifers	No detectable total coliforms/100 ml, 1 mg/l Cl ₂ residual (minimum values), Turbidity 2 NTU, TOC 2 mg/L, pH = 6.5-8.5, Other chemicals must meet drinking water standards.
<i>Recycled water rules</i> ⁶ (Idaho, USA)	N/A	Recycled water must meet IDAPA 58.01.11 “Ground Water Quality Rule”.
<i>Standards of reclaimed water quality</i> ⁷ (China)	N/A	Fecal coliforms 3 (1000 mL), Chromaticity color 15, Turbidity 5 NTU, no detectable odor, pH: 6.5-8.5, DO ≥ 1 mg/L, Hardness (as CaCO ₃) 450 mg/L, BOD ₅ 4 mg/L, COD _{Cr} 15 mg/L, TDS 1000 mg/L, NH ₃ -N 0.2 mg/L, NO ₂ ⁻ -N 0.02 mg/L, Hg 0.001 mg/L, Cd 0.01 mg/L, As 0.05 mg/L, Cr 0.05 mg/L, Pb 0.05 mg/L, Iron 0.3 mg/L, Mn 0.1 mg/L, Fluoride 1 mg/L, Cyanide 0.05 mg/L.

(To be continued)

Table 2.1 Required Water Quality for Managed Aquifer Recharge with Reclaimed Water

Water Reuse Regulations or Guidelines	Categories	Recharge Water Quality Limits
<i>Reuse of Treated Wastewater Guidance Manual</i> ⁸ (Pennsylvania, USA)	Direct injection	Fecal coliform < 2.2/100 mL (monthly average value) & 23/100 mL (maximum value), BOD <2 mg/L (monthly average value) & 5 mg/L (maximum value), TOC <1 mg/L (monthly average value), Turbidity <0.3 NTU (monthly average value) & 1 NTU (maximum value), TOX<0.2 mg/L (monthly average value), Total Nitrogen<10 mg/L (monthly average value), Other Contaminants must meet the primary and secondary drinking water standards.
	Infiltration basins	As described for direct injection, except for the following differences: BOD <2 mg/L (monthly average value) & 5 mg/L (maximum value), TOC <10 mg/L (monthly average value), Turbidity <2 NTU (monthly average value) & 5 NTU (maximum value).

References for the Table:

1. British Columbia Ministry of Environment, Lands and Parks (2012);
2. California Department of Public Health (2014);
3. Florida Department of Environmental Protection (2009);
4. NRMCC-EPHC-NHMRC (2009);
5. U.S. EPA. (2012)
6. Idaho Department of Environmental Quality (2009);
7. MWR (2006);
8. Pennsylvania Department of Environmental Protection (2012).

Table 2.2 Treatment Requirements and Setback Distances for Managed Aquifer Recharge with Reclaimed Water

Water Reuse Regulations or Guidelines	Category	Water treatments	Calculation of Setback distance
<i>Waste Management Act: Municipal Wastewater Regulation</i> ¹ (British Columbia, Canada)	Infiltration basin for indirect potable use	Advanced treatment with disinfection and nitrogen reduction	Based on type of nearest water body and daily maximum flow (ranges from 30 to 300 m).
<i>Groundwater Replenishment with Recycled Water</i> ² (California, USA)	Surface or subsurface application for indirect potable use	Treatment train should consist of at least three different treatments Wastewater dilution Soil aquifer treatment	Based on tracer study or numerical modelling data (ranges from 0.25 to 0.67 months).
<i>Reuse of Reclaimed Water and Land Application</i> ³ (Florida, USA)	Rapid infiltration basins/ Absorption fields	Secondary treatment Filtration Disinfection	Potable water supply wells: 500 feet (normal conditions) to 200 feet (favorable conditions) Water transmission facility to a public water supply well: 100 feet Storage ponds to potable water wells: 500 feet
	Injection to G-II ground water having TDS <3000 mg/L	Secondary treatment Filtration Disinfection Multiple barriers for control of pathogens & organics	Approved water intakes: 500 feet Potable water supply wells: 500 feet (normal conditions) to 1000 feet (salinity barriers)
	Injection to G-II ground water having TDS >3000 mg/L	Secondary treatment Filtration Disinfection	Approved water intakes: 500 feet Potable water supply wells: 500 feet (normal conditions) to 1000 feet (salinity barriers)

(To be continued)

Table 2.2 Required Treatments and Setback Distances for Managed Aquifer Recharge with Reclaimed Water

Water Reuse Regulations or Guidelines	Categories	Water treatments	Setback distances
<i>Australian Guidelines for water recycling: Managed Aquifer Recharge</i> ⁴ (Australia)	13 types	Soil aquifer treatment	N/A
<i>U.S.EPA 2012 Guidelines for Water Reuse</i> ⁵ (USA)	Groundwater recharge for non-potable uses	Site specific and use dependent Primary treatment for spreading Secondary treatment for injection	Site specific
	Groundwater recharge by spreading into potable aquifers	Secondary treatment Filtration Disinfection Soil aquifer treatment	Distance to nearest potable water extraction well that provides a minimum of 2 months retention time in the underground
	Groundwater recharge by injection into potable aquifers	Secondary treatment Filtration Disinfection Advanced water treatment	Distance to nearest potable water extraction well that provides a minimum of 2 months retention time in the underground
<i>Recycled water rules</i> ⁶ (Idaho, USA)	N/A	N/A	N/A
<i>Reuse of Treated Wastewater Guidance Manual</i> ⁷ (Pennsylvania, USA)	Direct injection	Secondary treatment Nitrification/Denitrification Coagulation, Filtration Reverse osmosis, Disinfection	N/A
	Infiltration basins	Secondary treatment Nitrification/Denitrification Filtration, Disinfection	N/A

(To be continued)

Table 2.2 Required Treatments and Setback Distances for Managed Aquifer Recharge with Reclaimed Water

Water Reuse Regulations or Guidelines	Categories	Water treatments	Setback distances
<i>Standards of reclaimed water quality</i> ⁸ (China)	N/A	N/A	N/A

References for the Table:

1. British Columbia Ministry of Environment, Lands and Parks (2012);
2. California Department of Public Health (2014);
3. Florida Department of Environmental Protection (2009);
4. NRMMC-EPHC-NHMRC (2009);
5. U.S. EPA. (2012)
6. Idaho Department of Environmental Quality (2009);
7. Pennsylvania Department of Environmental Protection (2012);
8. MWR (2006).

2.2.3 Establishment of a Regulatory Framework

Based on the summary and discussion of current regulations/guidelines for MAR with reclaimed water, this section proposes a regulatory framework for MAR implementation. Figure 2.4 shows an overview of a scheme for MAR with reclaimed water. The framework is comprised of three steps that include planning, design, and operation.

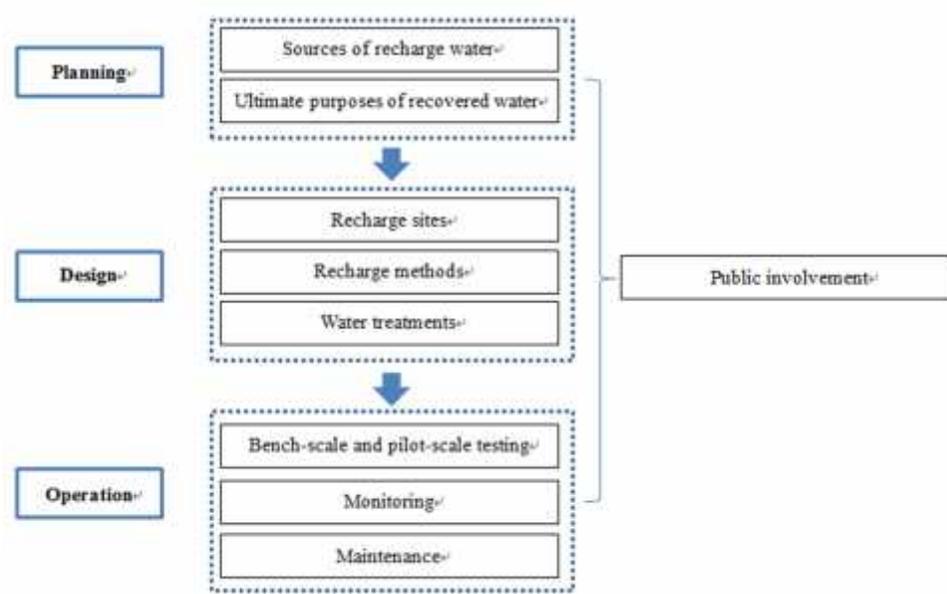


Figure 2.4 Regulatory Framework of MAR with Reclaimed Water

In the first stage, existing problems should be thoroughly analyzed to determine that there is a need to establish a MAR project. This step identifies the sources of recharge water and ultimate purposes of recovered water. The amount of recharge water and recovered water should be evaluated to ensure that water supply can exceed water demand. If the project plans to use reclaimed water as a source of recharge water, which mainly comes from wastewater and stormwater, and ultimate purposes such as potable, agricultural, or recreational uses may cause concerns, and therefore public involvement is important in the whole project implementation process.

After the project goal and scope have been determined, essential components in MAR project design should be done. The selection of recharge sites and recharge methods mainly depends on local geological and hydrogeological characteristics. A suitable recharge aquifer can not only ensure

adequate recharge rates, storage and recovery, but also provide additional natural water treatments. To control contaminants, the water treatment system is an essential design component in MAR. Water pre-treatment processes and underground retention distance/time are normally specified in the regulations/guidelines to ensure that both natural groundwater quality and recovered water quality requirements are met. In addition, the public are kept informed in the decision-making process for the design of MAR system to ensure that there is no risk to the public health or environment.

The final stage is construction, operation, and monitoring. Normally, before the construction of full-scale MAR systems, bench-scale and pilot-scale testing should be conducted to assess the system performance. The efficiency of artificial pre-treatment or post-treatment units and MAR simulation bottles or columns to remove contaminant can be tested in the labs. Design alternations such as specific treatment optimizations or recharging rate adjustments can then be made based on the test results and a testing report can be shown to the public. After the establishment of full-scale MAR system, routine monitoring and system maintenance should be performed to mitigate certain operating issues such as clogging or adverse monitoring results and operation reports can be assessed by the public.

2.3 MAR Case Studies

Until now, a number of MAR projects have been established all over the world. Almost all of them focus on solving the water shortage problem, but address different specific issues. The projects involve a wide range of recharge water sources, treatment methods, recharge methods and ultimate uses of recovered water. Various types of MAR have been applied, including aquifer storage and recovery in Salisbury, Australia; vadose zone wells in Phoenix, USA; bank filtration in Berlin, Germany; dune filtration in Amsterdam, The Netherlands; and infiltration ponds in the Burdekin Delta, Australia (Kazner *et al.*, 2012). Although many MAR projects have been established, sophisticated MAR guidelines or standards are still unavailable (Kazner *et al.*, 2012; Ward and Dillon, 2012). Therefore, reviewing previous MAR planning, designing, and management experiences is of crucial importance for the success of the future MAR projects. Since MAR with reclaimed water can effectively mitigate both water shortages and environmental pollution, this type of MAR project has

drawn growing interest. To learn lessons from existing practices, three case studies that have used MAR with reclaimed water will be discussed in detail under the proposed regulatory framework.

Montebello Forebay Groundwater Recharge Project (USA)

The Montebello Forebay Groundwater Recharge Project (MFGRP) is the oldest project planned for indirect potable reuse in California. Since 1962, this project has been recharging over 1.6 million acre-feet (1974 million m³) of recycled water to the Central Groundwater Basin, in order to provide a new potable water supply for Los Angeles County (U.S.EPA., 2012a).

In the planning stage, treated wastewater, surface water, and stormwater are used as the sources of recharge water (Gasca *et al.*, 2011). Mixing three types of water can dilute the concentrations of residual contaminants in the treated wastewater, thus increasing the safety and reliability of water supply. For the design of treatment and recharge facilities, treated wastewater accounts for 35% of the recharge water, and initially goes through conventional tertiary treatment which include filtration and chlorine disinfection, followed by nitrification/denitrification and UV disinfection to further improve the water quality (Lazarova, 2013). Two sets of spreading grounds, the Rio Hondo Coastal Spreading Grounds with 20 individual basins and San Gabriel Coastal Spreading Grounds with 3 individual basins, are used to percolate recharge water into aquifers (Gasca *et al.*, 2011). The selection of surface spreading sites can provide an additional natural treatment for the recharge water, and therefore obviate the needs of advanced water pre-treatment. During the operation, individual spreading basins are operated under wetting/drying cycles (U.S.EPA., 2012a). This operation mode optimizes the infiltration of water and prevents the development of vectors, thus ensuring continuous and effective performance. The extensive monitoring is conducted from the sources of recharge water to the final groundwater aquifers (U.S.EPA, 2012a). Therefore, the quality of groundwater can be protected and instant responses can be taken to deal with adverse monitoring results, such as the outburst of pathogens in water.

MFGRP is a typical MAR project, and thus, used as an example to show the key components in the MAR system. Through the analysis under the proposed regulatory framework, it can be shown that all elements are playing important roles for the success of MAR projects.

Orange County Groundwater Replenishment System (USA)

The Groundwater Replenishment System (GWRS) in Orange County, California, is another groundwater recharge project using recycled water in California. As the world's largest wastewater purification system for indirect potable reuse, GWRS provides a large amount of safe and high quality water for around 600,000 residents in north and central Orange County (Lazarova, 2013).

In this project, highly treated wastewater is recharged into aquifers through both direct injection and surface spreading to replenish groundwater basins and prevent seawater intrusion (U.S.EPA, 2012a). Therefore, the drinking water sources can be protected and water supply can be increased. The most innovative part of this case study is its design for water treatments. In order to produce high-quality recharge water, a state-of-the-art wastewater purification plant has been constructed. The plant uses a three-step treatment process consisting of microfiltration (MF), reverse osmosis (RO), and ultraviolet light (UV) with hydrogen peroxide to treat secondary effluent from the wastewater treatment plant (Wehner, 2010). This treatment train is being named as “full advanced treatment” in the recent California groundwater replenishment regulation (California Department of Public Health, 2014). This standard treatment train for potable reuse can remove different types of residual contaminants in treated wastewater. MF and RO respectively remove suspended or colloidal contaminants and dissolved contaminants. The final UV and peroxide treatment can disinfect microorganisms and oxidize organic compounds. Through the treatment, the quality of the reclaimed water exceeds all state and federal drinking water standards. Operating since January 2008, this project can produce up to 265,000 m³ of high-quality water every day (Lazarova, 2013). In addition, the effective public outreach through favorable media attention facilitates the project implementation from the conceptual plan to the final operation (Wehner, 2010).

GWRS is a perfect example to illustrate the effectiveness of advanced water treatments. From this case study, it can be seen that membrane filtration and advanced oxidation processes (AOPs) are the future of water reuse.

Salisbury Aquifer Storage, Transfer and Recovery Project (Australia)

Started in 2003, the Aquifer Storage, Transfer and Recovery (ASTR) project in Salisbury, Australia, is a demonstration MAR system for stormwater harvesting. Since the project was established,

Salisbury and regional towns have had the ability to store runoff from the short and intense precipitation events that occur from May to September, and therefore have a reliable alternative water source (Kazner *et al.*, 2009).

The system encompasses the Parafield Stormwater Harvesting Facility, which is used to collect and pre-treat stormwater, and the ASTR well field, which is used to inject and abstract water. In the harvesting system, stormwater from a 16.2 km² mixed industrial and residential catchment is collected and then diverted through two stormwater settling basins into a constructed wetland with a capacity of 25,000 m³ (Page *et al.*, 2010a; Page *et al.*, 2010b). The application of constructed wetlands provides a cost-effective and robust natural way to pre-treat stormwater. In the well field, four wells are used for injection and two wells are used for abstraction. The separation of these injection wells and abstraction wells gives a longer residence time to ensure the production of higher quality recovered water for irrigation (Kazner *et al.*, 2009). Since the storm harvesting and ASTR are all passive treatments, their performances cannot be easily controlled. To ensure the water quality, frequent sampling and monitoring are conducted (Kazner *et al.*, 2009). Currently, this site is used as a full-scale trial to evaluate the feasibility of potential drinking water production. Post-treatments which may include UV and chlorine disinfection are still under investigation (Page *et al.*, 2010c).

Salisbury ASTR project demonstrates the importance of natural system application in MAR systems. Since natural treatments are green technologies, which can reduce the human efforts and negative environmental impacts, these processes will be widely applied in future systems.

Summary of MAR with Reclaimed Water Case Studies

Besides the case studies mentioned above that show the importance of interdependence between MAR components, advanced water treatments, and natural treatments for MAR implementation, several other notable MAR with reclaimed water projects are also established in different parts of the world, including USA, Australia, Belgium, Italy, Spain, China, Israel (Table 2.3).

From the table, it can be seen that USA and Australia play the leading roles in MAR with reclaimed water. Because of environmental pollution and water shortage, treated wastewater is becoming more important as a source of recharge water. To reduce the concentrations of contaminants in wastewater and increase the water supply, other types of water such as stormwater or

surface water are often imported to mix with wastewater as the sources of recharge water. In terms of water treatment, additional advanced water treatment technologies, including high-pressure membrane filtration and advanced oxidation processes (AOPs), are included in pre- or post-recovery, to ensure the required level of contaminant removal is achieved or surpassed, due to their excellent ability to remove different types of contaminants. When the recharge method is surface spreading, SAT normally serve as an additional natural treatment to purify water. As for all MAR systems, recharge methods, sources of recharge water, water treatments, and ultimate uses of recovered water have a close relationship. For example, if the ultimate use of the recovered water is for potable use, some drinking water treatment processes such as coagulation, sedimentation, filtration, and disinfection can serve as the pre-treatment method, and surface spreading can be used as the recharge method to ensure the quality of the recovered water. In all cases, communication and acceptance by the public are needed to ensure that environmental and public health concerns are addressed.

Table 2.3 Examples of MAR with Reclaimed Water Projects

Name	Recharge methods	Sources of recharge water	Water treatments	Ultimate uses of recovered water
Alamitos saltwater barrier project (California, USA)	Direct injection	Imported surface water Treated wastewater	Microfiltration/reverse osmosis/ UV disinfection	Seawater intrusion prevention
Chino basin groundwater recharge project (California, USA)	Surface spreading	Imported surface water Treated wastewater Stormwater	Tertiary treatment Soil aquifer treatments	Potable use
Dominguez gap barrier project (California, USA)	Direct injection	Imported surface water Treated wastewater	Microfiltration/reverse osmosis/ UV disinfection	Seawater intrusion prevention
Montebello forebay groundwater recharge project (California, USA)	Surface spreading	Imported surface water Treated wastewater Stormwater	Tertiary treatment Soil aquifer treatments	Potable use
Orange county groundwater replenishment system (California, USA)	Surface spreading Direct injection	Treated wastewater	Microfiltration/reverse osmosis/ ultraviolet light with hydrogen peroxide Soil aquifer treatments	Potable use Seawater intrusion prevention
West coast basin barrier project (California, USA)	Direct injection	Imported potable water Treated wastewater	Microfiltration/reverse osmosis/ UV disinfection	Seawater intrusion prevention
City of Desin aquifer storage and recovery project (Florida, USA)	Direct injection	Treated wastewater	Flocculation/filtration/ high level disinfection	Landscape irrigation
Winter Garden “Water Conserv II ” project (Florida, USA)	Surface spreading	Treated wastewater	Ozone treatment/reverse osmosis Soil aquifer treatments	Agricultural irrigation
Northern Adelaide Plains aquifer recharge project (Australia)	Direct injection	Treated wastewater	Tertiary treatment	Irrigation

(To be continued)

Table 2.3 Examples of MAR with Reclaimed Water Projects

Name	Recharge methods	Sources of recharge water	Water treatments	Ultimate uses of recovered water
Salisbury aquifer recharge project (South Australia, Australia)	Direct injection	Stormwater	Wetland treatment	Irrigation/Industrial uses Potential drinking use
Perth aquifer recharge project (Western Australia, Australia)	Surface spreading	Treated wastewater	Microfiltration/reverse osmosis Soil aquifer treatments	Potable use
Sydney aquifer recharge project (New South Wales, Australia)	Surface spreading	Treated wastewater Stormwater	Tertiary treatment Soil aquifer treatments	Saltwater intrusion prevention
St-André aquifer recharge project (Flanders, Belgium)	Surface spreading	Treated wastewater	Ultrafiltration/reverse osmosis/ UV disinfection Soil aquifer treatments	Potable use
Nardó karstic aquifer recharge project (Apulia, Italy)	Direct injection	Treated wastewater	Conventional activated sludge process	Irrigation Seawater intrusion prevention
Sabadell aquifer recharge project (Catalonia, Spain)	Surface spreading	Treated wastewater	Conventional activated sludge process Soil aquifer treatments	Non-potable uses such as parks irrigation, streets cleaning
Zhengzhou groundwater recharge project (Henan, China)	Surface spreading	Treated wastewater	Coagulation/filtration/adsorption/disinfection/ artificial wetland Soil aquifer treatments	Fishery Agriculture Industry
Gaobeidian aquifer recharge project (Beijing, China)	Direct injection	Treated wastewater	Coagulation/sedimentation/ rapid sand filtration/ozonation	Under investigation
Shafdan aquifer recharge project (Israel)	Surface spreading	Treated wastewater	Conventional activated sludge process/ ultrafiltration Soil aquifer treatments	Irrigation

2.4 Knowledge Gaps and Research Needs

There is currently a knowledge gap with regards to the inadequate regulatory systems for MAR with reclaimed water, and this creates a challenge for the implementation of MAR projects. Although some water reuse regulations or guidelines have included requirements for MAR (Florida Department of Environmental Protection, 1999; MWR, 2006; Idaho Department of Environmental Quality, 2009; NRMMC-EPHC-NHMRC, 2009a; British Columbia Ministry of Environment, Lands and Parks, 2012; Pennsylvania Department of Environmental Protection, 2012; U.S.EPA, 2012a; California Department of Public Health, 2014), limited specified planning procedures or requirements are available in the documents. Therefore, the establishment of specific criteria and standards governing MAR with reclaimed water is encouraged.

In addition, the inadequate understanding and control of underground processes also hampers MAR design and operation. Although many studies are investigating the removal of contaminants during recharge processes (e.g. Montgomery-Brown *et al.*, 2003; Quanrud *et al.*, 2003; Zhang *et al.*, 2005) and recharge operation or design issues (e.g. Bouwer, 1996; Bouwer, 2002; Vanderzalm *et al.*, 2010), system performance is quite site specific and standards for MAR are unavailable. Thus, more work should be conducted in order to establish clear design and operation criteria for MAR.

Finally, a complete quantitative risk assessment of managed aquifer recharge should be developed. Although Australian water reuse guidelines have established a risk assessment framework, and previous studies have taken qualitative and preliminary quantitative approaches to assess the risks associated with MAR projects (Swierc *et al.*, 2005; Page *et al.*, 2008; NRMMC-EPHC-NHMRC, 2009a), mature quantitative risk assessments are still not available to support the feasibility assessment of new MAR projects. Future studies should focus on developing a quantitative risk assessment approach for MAR.

2.5 Summary and Conclusions

The problem of water shortages places a great value for water reclamation and reuse. Managed aquifer recharge with reclaimed water is a very beneficial water reuse application but has a wide range of challenges for its implementation. Within an MAR system, diverse aspects including

planning, technical design or operational considerations, and political issues should be considered. To date, a number of water reuse regulations or guidelines have been established worldwide and some of them include requirements to govern the implementation of MAR projects. MAR with reclaimed water projects have been implemented in many countries such as USA, Australia, Belgium, Israel, and China. Suggestions or lessons learned from current water reuse regulations/guidelines and MAR case studies are as follows:

- Five components (sources of recharge water, recharge methods, recharge sites, water treatments, and ultimate uses of recovered water) can be used to assess MAR systems. Water quality is an essential consideration and influences the key factors for MAR systems.
- A review of the available water reuse guidelines or regulations identified different planning, design and operational requirements for MAR with reclaimed water. Based on their requirements, a regulatory MAR framework was proposed.
- Several established MAR with reclaimed water projects can serve as a reference for the future implementation of MAR projects.
- Specific regulatory or design criteria for the establishment of MAR systems and a complete quantitative risk assessment framework for the evaluation and operation of MAR systems should be established in the future.

Chapter 3

Background Information

3.1 Study Area Characterization

The regional municipality of Halton is a community situated in southern Ontario in the southwest part of the Greater Toronto Area (“GTA”). The Region has the land area of 964.01 km², comprising the city of Burlington and the towns of Oakville, Milton, and Halton Hills. Located to the north, the towns of Milton and Halton Hills are more rural, compared with the town of Oakville and city of Burlington which are located to the south and largely urban. With one of the highest population growth rates in the country, the region of Halton experienced a growth rate of 14.2% between 2006 and 2011 (Statistics Canada, 2012). Such a high population growth places a great pressure on Halton’s water and wastewater systems.

For some areas in the southern part of Halton, the potable water supply depends on Lake Ontario. However, for other northern areas, the water supplies rely on groundwater from aquifers. Similarly, WWTPs in the southern area of Halton discharge treated wastewater effluents to the lake. WWTPs in the northern part of the Region discharge treated effluents into neighboring streams such as Silver Creek and Black Creek. Black Creek is a major tributary of Silver Creek, and they connect west of Georgetown. Silver Creek flows to the Credit River and then into Lake Ontario (Credit Valley Conservation, 2009).

A significant part of northern Halton is located within the Black Creek subwatershed in the middle section of the Credit River watershed, as shown in Figure 3.1 (Credit Valley Conservation, 2009). The Black Creek subwatershed is adjacent to the Silver Creek subwatershed. Both are bisected by the Niagara Escarpment, and these two subwatersheds share similar features, including hydrology, flow and climate conditions (Credit Valley Conservation, 2009).

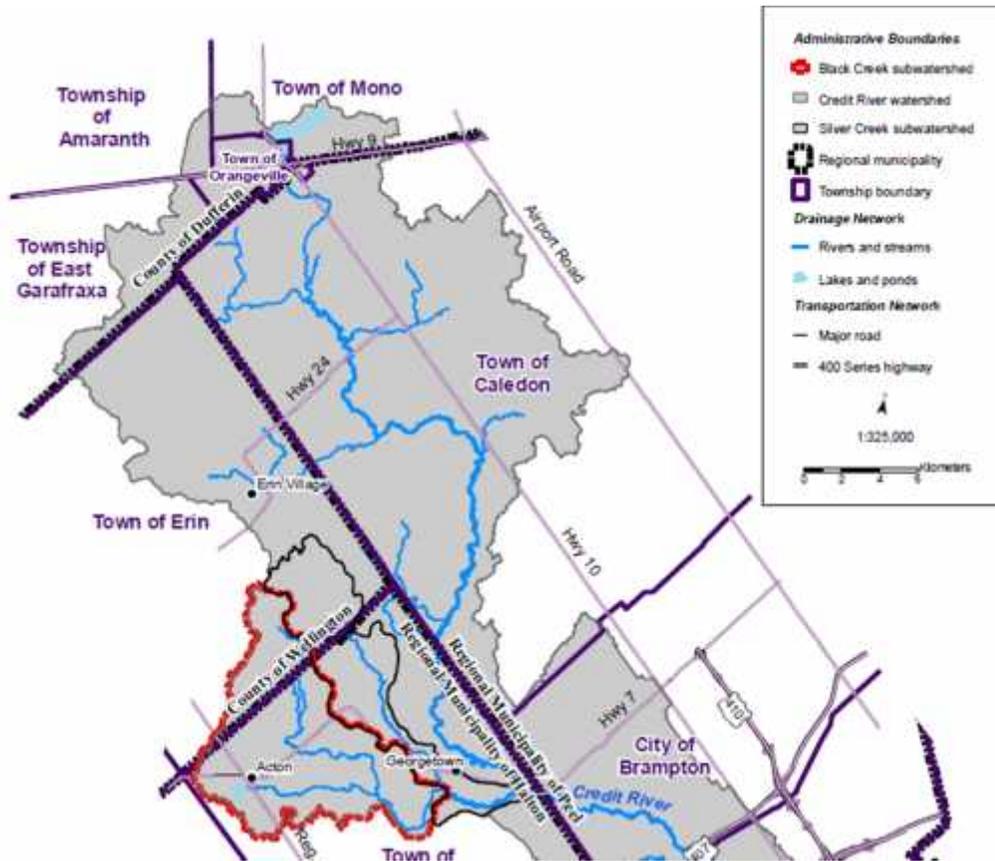


Figure 3.1 Black Creek Subwatershed (Adapted from Credit Valley Conservation, 2009)

The Black Creek subwatershed is an approximately 79.28 km² area that covers the entire town of Acton and part of Georgetown (Credit Valley Conservation, 2009). Bisected by the Niagara Escarpment, the subwatershed is divided into two distinctly different areas. The subsurface geology in the area below the Escarpment is dominated by impermeable Halton till, while area above the Escarpment, is composed of permeable materials including fine sand and gravels. The high permeability of soil indicates this area may be suitable for aquifer recharge (Credit Valley Conservation, 2009).

3.2 Water Supply Systems

Water supplies that use groundwater as a source are typically of high quality and require little treatment before distribution. In Halton Region, a typical treatment system for well water involves ultraviolet (UV) light and chlorine disinfection, and fluoride is added to reduce tooth decay. In some cases, the water is further treated by greensand filters and cartridge filtration for manganese and iron removal to address aesthetic issues. Finally, water is pumped to a reservoir and then into the distribution system (The Regional Municipality of Halton, 2014).

Based on the future planning and development targets, regional population and employment projections to 2031 are presented in the report “Halton Region Sustainable Halton Water and Wastewater Master Plan—Executive Summary (2011)”. The residential population is expected to grow from 493,045 in 2011 to 752,537 in 2031 and employment population is expected to grow from 250,932 in 2011 to 390,000 in 2031 (The Regional Municipality of Halton, 2011a). The report states that some areas in Halton region need to be expanded to accommodate the residential and employment growth, and associated additional water demands must be met. To service the build-out of the existing urban areas, a feasible strategy to increase capacity is needed. Alternatives to increase water supplies have been evaluated, and various options such as demand management and water conservation, existing well field expansions, establishment of new surface water or groundwater sources, water delivery from another community, and MAR technologies have all been proposed. (The Regional Municipality of Halton, 2011a).

3.3 Wastewater Treatment Systems

3.3.1 WWTP Master Plan

To accommodate build-out of the existing urban areas in Halton Region, additional wastewater treatment capacity may be needed (The Regional Municipality of Halton, 2011c). Various alternatives include improving receiving stream assimilative capacity, diverting wastewater to other existing WWTPs in the Region, reducing infiltration/inflow to plants, upgrading existing plants, constructing new WWTPs, and reusing wastewater effluent. Currently, effluents from WWTPs in the northern area of Halton Region are discharged into rivers or streams. Due to the sensitivity of rivers to contaminant

loads and temperature, increases in wastewater effluent loading must be thoroughly evaluated (The Regional Municipality of Halton, 2011c). To minimize undesirable effects on the natural environment and ensure a reliable water supply, aquifer recharge was recognized as a potential option for indirect potable reuse (The Regional Municipality of Halton, 2011a).

Aquifer recharge has been considered to a lesser extent in Canada, but has been implemented in other countries including the United States (refer to Chapter 2). Therefore, more information is required to better evaluate this option, and in particular treatment options that would be required to minimize the impacts of recharge water on the groundwater or human health are of crucial importance. Aquifer recharge for Halton Region could potentially involve two options. The first option is to use surface water to recharge aquifers via surface spreading. The second option is to recharge highly treated wastewater effluent from the WWTP to aquifers by surface spreading basins, and this was the option evaluated in this thesis. The overall objective of the current project is to investigate water pre-treatment technologies for aquifer recharge using reclaimed water. Other important factors for MAR, including the location, recharge method, subsurface and aquifer hydrogeology, and recovery method are outside the scope of this study.

3.3.2 Wastewater Treatment Plant Case Study Data

To conduct a feasibility study on treatment options required for MAR with reclaimed water, example water quality data from a typical WWTP was provided by Halton Region for the purpose of this research project. This case study data is based on a WWTP system that utilizes an activated sludge treatment with tertiary filtration and ultraviolet (UV) disinfection. A typical system would consist of following components: inlet works; sewage pumping; primary clarification; biological treatment; secondary clarification; chemical dosing; tertiary filtration; UV disinfection; sludge digestion. The purpose of each component is as follows:

Inlet Works. The inlet works use screens to remove large objects, such as rags, grit, and plastics, from raw wastewater.

Sewage Pumping. The pump station delivers flow from the inlet works into the plant.

Primary Clarification. The main purpose of this treatment step is to remove excess solids before biological treatment.

Biological Treatment. Biological treatment utilizes activated sludge with nitrification to remove dissolved organic matter from wastewater.

Secondary Clarification. Secondary clarification process is designed to remove activated sludge biomass from aeration effluent.

Chemical Dosing. Alum is typically added to improve settling performance and facilitate the phosphorus precipitation. Alum is added to wastewater in the primary and secondary clarifiers.

Tertiary Filtration. This process mainly removes residual suspended solids and precipitated phosphorous.

UV Disinfection. This advanced wastewater disinfection technique is used for inactivating microorganisms including pathogens in the wastewater effluent.

Sludge Digestion. The sludge digestion reduces the total volume of waste sludge in the treatment process and stabilizes the waste for later off-site disposal.

Example effluent water quality data were provided by Halton Region, and is described in Chapter 4. Additional assumptions for the case study are that the wastewater plant would receive mainly household waste and little or no discharge from manufacturing or industry. Also, it was assumed that the treated waste would be discharged into a river, and therefore the plant effluent would meet the surface water quality objectives for this type of receiving environment.

Chapter 4

Identification of Critical Contaminants in Wastewater Effluents for MAR

4.1 Introduction

MAR with reclaimed water is a beneficial tool being applied worldwide to replenish groundwater basins and provide alternative potable water sources. Many MAR projects are recharging treated wastewater into aquifers to increase water supply, such as the Orange County groundwater replenishment system in the USA (Lazarova, 2013), the St-André aquifer recharge project in Belgium (Kazner *et al.*, 2009), and the Perth aquifer recharge project in Australia (Page *et al.*, 2010a). Among different types of reclaimed water sources, municipal wastewater treatment plant effluent has been more frequently used as the recharge water source due to its wide availability. However, using wastewater effluent as the source of recharge water may pose a risk to the safety of groundwater since effluents may contain residual wastewater contaminants that are not effectively removed by conventional wastewater treatments, and trace contaminants that have low concentrations but may have adverse effects on human health (Díaz-Cruz and Barceló, 2008; U.S.EPA, 2012a). Therefore, it is quite important to identify significant contaminants in wastewater effluent which need additional treatment for MAR.

Most water reuse regulatory documents (Florida Department of Environmental Protection, 1999; MWR, 2006; Idaho Department of Environmental Quality, 2009; NRMHC-EPHC-NHMRC, 2009a; British Columbia Ministry of Environment, Lands and Parks, 2012; Pennsylvania Department of Environmental Protection, 2012; U.S.EPA, 2012a; California Department of Public Health, 2014) specify values for typical wastewater parameters such as microbial indicators (*E.coli*, total coliforms), biochemical oxygen demand (BOD), suspended solids (SS), and nutrients (carbon, nitrogen and phosphorus compounds). The Australian water reuse guideline is the only document that doesn't identify specific limits, but instead risk assessment procedures are used to determine the water quality targets for MAR. To ensure the safety of indirect potable reuse, some inorganic and organic chemicals are also included in the regulations or guidelines. For example, the Florida and Idaho documents state that drinking or environmental water standards should be used as the limits for

organics or inorganics. Only the California and China regulations set specific values for a range of inorganic and organic compounds. In Canada, only British Columbia has established MAR requirements in a regulation, but no specific contaminants are included. Hence, it is difficult to determine which contaminants are important for MAR based on the current Canadian regulations or guidelines. Although some of the worldwide water reuse regulations/guidelines can serve as a reference, the data required may not be available in wastewater effluents since routine monitoring for these contaminants, especially organics, may not be regulated for WWTP effluents. Additionally, these water reuse regulatory documents don't cover emerging contaminants, which often exist in wastewater effluents and are of potential concern. Therefore, to ensure the safety of MAR with reclaimed water, residual contaminants in wastewater effluents should be considered for removal through additional treatment.

The removal of residual contaminants in wastewater effluents depends on the contaminant concentrations, physicochemical characteristics, water characteristics, treatment options and operating conditions. Since the number of potential contaminants is large, it is difficult to measure and evaluate the removal efficiency of each contaminant by different treatment alternatives. Therefore, it is more efficient to select some representative contaminants, which have higher occurrences in wastewater effluents, more negative ecological effects on groundwater and severe health impacts on human health. These representative compounds can then be used for the assessment of treatment technologies. For this reason, an approach to identify critical contaminants in wastewater effluent for MAR is needed.

Currently, several studies have developed methods to screen and select priority and emerging compounds based on designed multi-criteria ranking systems (Arnot and Mackay, 2008; Eriksson *et al.*, 2008; Muñoz *et al.*, 2008; Kumar and Xagorarakis, 2010; Jean *et al.*, 2012; Sui *et al.*, 2012; Li *et al.*, 2014). Each of these studies made a short list of chemicals for monitoring purposes, including priority xenobiotic organic compounds in sewage sludge which is used for agriculture land application (Eriksson *et al.*, 2008), priority pollutants in urban wastewater which can cause potential environmental impacts (Sui *et al.*, 2012), priority emerging organic contaminants in surface and finished drinking waters (Kumar and Xagorarakis, 2010; Sui *et al.*, 2012), and priority bioaccumulable pharmaceutical substances discharged in hospital effluents (Jean *et al.*, 2012). Several screening

criteria such as occurrence, biodegradability, ecological and health effects are used to screen priority chemicals. Among these studies, Li *et al* (2014) developed a ranking system to select priority organics for groundwater recharge. However, this study only included the assessment of organic contaminants at one site in China. Since other types of contaminants besides organics may also be of concern for MAR with reclaimed water, and priority contaminants may vary from country to country, a multi-criteria approach to select critical contaminants for MAR with reclaimed water in Canada should be developed.

In this study, a system is proposed to select the critical contaminants for MAR with reclaimed water. Based on current regulations or guidelines, WWTP effluent monitoring data, and literature data, a list of priority contaminants is developed which have the greatest possibility to exist in municipal wastewater effluent and cause potential adverse effects. The goal for establishing a short list of priority contaminants was to use these data to assess removal through additional water treatment processes. This removal assessment is performed in Chapter 5.

4.2 Approach

The following sections outline the development of a multi-criteria system and data collection for contaminants in wastewater effluent. First, a list of required water quality parameter targets for MAR was defined based on current regulations and guidelines. Then, critical contaminants for MAR with reclaimed water were selected in three parts: (1) predominant contaminants were identified based on data from a WWTP effluent; (2) additional organic and microbial contaminants were selected based on compounds that are included in regulations/guidelines but not routinely monitored in WWTP; (3) specific emerging contaminants were identified, which are not currently regulated but may be important for MAR. This study used example data from a WWTP in southern Ontario, Canada, but the approach and selection of contaminant limits for MAR can be generally applied. A description of the example WWTP system used as a case study for this research is provided in Chapter 3. The system described is typical for a WWTP providing conventional tertiary treatment of primarily household waste.

4.3 Determination of Water Quality Targets for Recharge Water

Due to a lack of specific requirements of contaminant limits for MAR in Canada, the required reclaimed water quality parameters for MAR should be defined. The objectives of determining water quality targets include the prevention of groundwater contamination and the guarantee of potable quality for recovered water.

Since most municipalities in Ontario that rely on groundwater sources for potable water supplies take water from the aquifers which contain high quality groundwater, the raw groundwater normally either exceeds drinking water standards or just needs to be treated to remove iron/manganese and disinfected before distribution (The City of Guelph, 2013; The Regional Municipality of Halton, 2014; The Region of Waterloo, 2013). Therefore, to protect the groundwater quality, drinking water standards can serve as a reference to determine recharge water quality. When reclaimed water is recharged into aquifers, the underground aquatic ecosystem may be adversely impacted. To control and prevent such pollution, the Ontario Provincial Water Quality Objectives (PWQO) (Ontario Ministry of the Environment, 1994) can also be used as guidance for the recharge water quality target determination. Since MAR with reclaimed water is an option for indirect potable reuse, worldwide water reuse regulations/guidelines which contain MAR requirements can also be helpful to decide the recharge water quality targets and ensure the potable water quality of recovered water. Although the Wastewater Systems Effluent Regulations (Government of Canada, 2014) specify limits for some wastewater quality parameters such as carbonaceous biochemical oxygen demand (CBOD) and suspended solids (SS), the specified parameters in the document have higher limits than those in water reuse regulations or PWQO since this regulation is applied to the discharge of effluents from wastewater systems. Therefore, this regulation was not selected as reference.

Through analyzing and screening regulations/guidelines, the following ten documents were used as references to determine the recharge water quality targets:

- *Guidelines for Canadian Drinking Water Quality* (Health Canada, 2012d).
- *Ontario Drinking Water Quality Standards* (O.Reg. 169/03 & O.Reg. 170/03) (Ontario Ministry of the Environment, 2002).
- *Water Management: Policies, guidelines, provincial water quality objectives of the Ministry of the Environment* (Ontario Ministry of the Environment, 1994).

- *Waste Management Act - Municipal Wastewater Regulation* (British Columbia Ministry of Environment, Lands and Parks, 2012).
- *Groundwater Replenishment with Recycled Water* (California Department of Public Health, 2014)
- *Reuse of Reclaimed Water and Land Application* (Florida Department of Environmental Protection, 1999).
- *USEPA 2012 Guidelines for Water Reuse* (U.S. EPA, 2012).
- *Recycled Water Rules* (Idaho Department of Environmental Quality, 2009).
- *Reuse of Treated Wastewater Guidance Manual* (Pennsylvania Department of Environmental Protection, 2012).
- *Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Managed Aquifer Recharge* (NRMMC-EPHC-NHMRC, 2009a).

Wastewater quality parameters typically measure indicators of water quality, and these are the values included in most water reuse regulations or guidelines. According to Table 4.1, these wastewater quality parameters include total coliforms, fecal coliforms, total suspended solids (TSS), biochemical oxygen demand (BOD₅)/carbonaceous biochemical oxygen demand (CBOD₅), total nitrogen, total organic carbon (TOC), and total organic halogen (TOX). Turbidity is also regulated in seven regulations/guidelines. Different regulatory documents often specify different limits for the same parameter. For microbial parameters, the U.S. EPA and British Columbia regulations have the strictest requirements for coliforms, while others have relatively higher values. For suspended particles, the British Columbia and Florida regulations specify the lowest TSS limit. The Pennsylvania regulation specifies the lowest limit for turbidity, which is similar with the turbidity limits in drinking water standards. For the nutrient indicators, the Pennsylvania regulation has the lowest limit for BOD, California has the lowest limit for TOC, and the lowest limit for total nitrogen is in the Idaho regulation. It is interesting to see that to limit the concentration of disinfection byproducts, TOX is also regulated in the regulations, with the lowest values in both Florida and Pennsylvania regulations. In Table 4.1, the most stringent value for each parameter is bold and underlined.

Table 4.1 Summary of Typical Reclaimed Water Quality Parameter Limits for MAR

Parameters	British Columbia ¹	USEPA ²	California ³	Florida ⁴	Idaho ⁵	Pennsylvania ⁶	Australia ⁷
Total coliforms	N/A	<u>None detectable</u> <u>/100mL</u>	2.2/100 mL (7 day med) & 23/100 mL (no more than one in 30 day) & 240/100 mL (max)	4/100 mL (max)	2.2/100 mL (7 day med) & 23/100 mL (any sample)	N/A	N/A
Fecal coliforms	1 CFU/100 mL (7 day med) or 2.2 MPN/100 mL (any sample)	N/A	N/A	N/A	N/A	2.2/100 mL (mon avg) & 23/100 mL (max)	N/A
TSS	<u>5 mg/L (max)</u>	N/A	N/A	5 mg/L (max)	N/A	N/A	N/A
BOD ₅ /CBOD ₅	BOD ₅ : 5 mg/L (max)	N/A	N/A	CBOD ₅ : 20 mg/L (anu avg) & 30 mg/L (mon avg) & 45 mg/L (wk avg) & 60 mg/L (max) &	BOD ₅ : 5 mg/L (mon ari mean)	<u>BOD₅:</u> <u>2 mg/L</u> <u>(mon avg) &</u> <u>5 mg/L (max)</u>	N/A
Total Nitrogen	20 mg/L (avg)	N/A	10 mg/L (avg of two consecutive samples)	10 mg/L (anu avg)	<u>10 mg/L (max)</u>	10 mg/L (mon avg)	N/A
TOC	N/A	2 mg/L (max)	<u>0.5 mg/L (avg)</u>	3 mg/L (mon avg) & 5 mg/L (max)	N/A	1 mg/L (mon avg)	N/A
TOX	N/A	N/A	N/A	<u>0.2 mg/L (mon avg)</u>	N/A	0.2 mg/L (mon avg)	N/A

(To be continued)

Table 4.1 Summary of Typical Reclaimed Water Quality Parameter Limits for MAR

Parameters	British Columbia ¹	USEPA ²	California ³	Florida ⁴	Idaho ⁵	Pennsylvania ⁶	Australia ⁷
Turbidity	1 NTU (max)	2 NTU (max)	2 NTU (avg) media filters 10 NTU (max) media filters 0.2 NTU (avg) membrane filters 0.5 NTU (max) membrane filters	Case-by-case (generally 2 to 2.5 NTU)	2 NTU (daily arithmetic mean) media filters 5 NTU (max) media filters 0.2 NTU (avg) membrane filters 0.5 NTU (max) membrane filters	<u>0.3 NTU</u> <u>(mon avg)</u> <u>1 NTU</u> <u>(max)</u>	1 NTU (max)

7 day med: 7 day monitoring data median value; anu avg: annual average value; avg: average value; max: maximum value; mon ari mean: monthly arithmetic mean from weekly composite sampling; mon avg: monthly average; N/A: No value; wk avg: weekly average

References for the table:

1. British Columbia Ministry of Environment, Lands and Parks, 2012;
2. U.S.EPA, 2012a;
3. California Department of Public Health, 2014;
4. Florida Department of Environmental Protection, 1999;
5. Idaho Department of Environmental Quality, 2009;
6. Pennsylvania Department of Environmental Protection, 2012;
7. NRMCC-EPHC-NHMRC, 2009a.

To prevent groundwater contamination and ensure recovered water quality, the most stringent limit for each parameter (bold and underlined in Table 4.1) is selected and summarized in Table 4.2. Since the lowest value for total coliforms was none detectable/100 mL, the same value was selected for fecal coliforms, to be consistent with water quality limits. It is important to note that for the parameter of BOD₅/CBOD₅, the BOD₅ limit used in the Pennsylvania regulation was selected, and that separate values for BOD₅ and CBOD₅ were not used. Most regulations included only BOD₅, and only the Florida regulation specified a CBOD₅ value of 20 mg/L, which is 3 times larger than BOD₅ limits required in other regulatory documents. Since it was reported that the normal value of CBOD₅/BOD₅ ratio is around 0.9 (Water Environment Foundation, 2006), the more stringent limit for BOD₅ was used for both BOD₅ and CBOD₅.

Table 4.2 Defined Typical Reclaimed Water Quality Limits for MAR

Typical reclaimed water parameter	Water quality limits
Total coliforms	None detectable/100 mL
Fecal coliforms	None detectable /100 mL
TSS	5 mg/L (max)
BOD ₅ /CBOD ₅	2 mg/L (mon avg) & 5 mg/L (max)
TOC	0.5 mg/L (avg)
TOX	0.2 mg/L (mon avg)
Turbidity	0.3 NTU (mon avg) & 1 NTU (max)

avg: average value; max: maximum value; mon avg: monthly average value

Limits for specific microbial and chemical contaminants are included in three water reuse guidelines (California, Florida and Idaho), and these were compared with the Ontario Provincial Water Quality Objectives (Ontario Ministry of the Environment, 1994), the Ontario drinking water regulations (Ontario Ministry of the Environment, 2002) and Health Canada drinking water guideline (Health Canada, 2012d) (Table 4.3). In terms of microorganisms, *E.coli.*, total coliforms, enteric viruses, *Giardia* cysts, and *Cryptosporidium*

oocysts are typically included in the regulations/guidelines. *E.coli* and total coliforms are used to indicate that pathogens may be present, and are set with a concentration limit (none detectable/100 mL). However, enteric viruses, *Giardia* cysts, and *Cryptosporidium* oocysts are set based on treatment goals (the achievement of which is determined by measuring a surrogate parameter such as turbidity for a given process), since these types of microorganisms currently cannot be accurately monitored in water, and the safety limits may vary depending on different factors that include features of host, pathogen, and environment (Health Canada, 2009; Health Canada, 2011). The removal objective for enteric viruses and protozoa in the Ontario and Health Canada treatment objectives are based on treating surface water for drinking water purposes. Only the California reuse guideline sets treatment objectives for viruses or protozoa based on treating raw sewage.

For chemicals, there are in total 31 inorganic chemicals and 95 organic chemicals have been included in water quality regulations and guidelines (Table 4.3). Ontario and Health Canada drinking water standards normally set the same limits for each contaminant and only three particular contaminants including arsenic, carbon tetrachloride (CTC), and N-nitrosodimethylamine (NDMA) have different limits. This may be due in part to the fact that Health Canada has more recently amended limits for certain contaminants, and these data have not as yet been incorporated into the Ontario regulations. As well, 18 contaminants are included only in the Ontario document while 10 are included only in the Health Canada document. In certain cases, this is because Health Canada has added limits for compounds based on aesthetic considerations (e.g. chloride, iron, manganese), or has removed contaminants that are no longer registered for use in Canada or mixtures that are addressed individually (e.g. aldicarb, dinoseb, parathion). Values similar to the Ontario and Health Canada standards can also be found in California, Florida and Idaho water reuse regulations, while California codes usually specify the most stringent values. Due to the high level of environmental protection in Ontario, Ontario Provincial Water Quality Objectives (PWQO) are set based on the lowest effect concentration reported for aquatic toxicity, bioaccumulation, and mutagenicity (Ontario Ministry of the Environment, 1994), and therefore are generally

lower than the required limits in other documents. As well, the PWQO sets limits for additional chemicals that could impact the environment at levels lower than those that would give rise to human health effects, including ammonia, phosphorus, chlorine, and certain metals (cobalt, molybdenum).

Based on the summary of microbial and chemical parameter limits regulated in different documents in Table 4.3, the water quality parameter targets for MAR can be defined (bold and underlined in Table 4.3). In terms of microorganisms, the most stringent limits set for *E.coli* and total coliforms among the regulations are ‘none detectable’. It can be seen that treatment goals for enteric viruses, *Giardia* cysts, and *Cryptosporidium* oocysts are quite different in the Health Canada and California documents since their reduction calculations are based on different types of water sources. The Health Canada guideline uses raw surface water or groundwater as the starting point while the California regulation uses raw wastewater. However, the present study will evaluate the treatment requirements for treated wastewater effluent, which is another type of water source. Therefore, water treatment goals for these pathogens should be redefined.

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Microbial	<i>E. coli</i>	<u>None detectable</u>	None detectable /100 mL	100 <i>E. coli</i> per 100 mL	N/A	N/A	1 per 100 mL
	Total coliforms	<u>None detectable</u>	None detectable /100 mL	NA	N/A	4/100 mL	2.2/100 mL (7 day med) & 23/100 mL (any sample)
	<i>Giardia</i> & <i>Cryptosporidium</i>	4-log reduction <i>Giardia</i> cysts 2-log reduction <i>Crypto</i> oocysts ⁷	Minimum 3-log reduction ⁷	N/A	10-log reduction ⁸	N/A	N/A
	Enteric viruses	4-log reduction ⁷	Minimum 4-log reduction ⁷	N/A	12-log reduction ⁸	N/A	N/A
Inorganic Chemicals	Aluminum	N/A	<u>0.1 mg/L</u>	At pH 4.5-5.5, 0.015 mg/L At pH 6.5-9, 0.075 mg/L At pH 5.5-6.5, ≤10% Natural Background	1 mg/L	0.2 mg/L	0.2 mg/L
	Ammonia	N/A	N/A	<u>0.05 mg/L</u>	N/A	N/A	N/A
	Antimony	<u>0.006 mg/L</u>	0.006 mg/L	0.02 mg/L	0.006 mg/L	0.006 mg/L	0.006 mg/L

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Inorganic Chemicals	Arsenic	0.025 mg/L	<u>0.01 mg/L</u>	0.005 mg/L	0.05 mg/L	0.01 mg/L	0.05 mg/L
	Asbestos	N/A	N/A	N/A	<u>7MFL</u>	7MFL	7MFL
	Barium	<u>1 mg/L</u>	1 mg/L	N/A	1 mg/L	2 mg/L	2 mg/L
	Beryllium	N/A	N/A	Hardness (CaCO ₃ , mg/L) <75, 0.011 mg/L >75, 1.1 mg/L	<u>0.004 mg/L</u>	0.004 mg/L	0.004 mg/L
	Boron	<u>5 mg/L</u>	5 mg/L	0.2 mg/L	N/A	N/A	N/A
	Bromate	<u>0.01 mg/L</u>	0.01 mg/L	N/A	N/A	N/A	N/A
	Cadmium	<u>0.005 mg/L</u>	0.005 mg/L	Hardness (CaCO ₃ , mg/L) 0-100, 0.0001 mg/L >100, 0.0005 mg/L	0.005 mg/L	0.005 mg/L	0.005 mg/L
	Chloramines	<u>3 mg/L</u>	3 mg/L	N/A	N/A	N/A	N/A
	Chromium	<u>0.05 mg/L</u>	0.05 mg/L	Cr VI, 0.001 mg/L Cr III, 0.0089 mg/L	0.05 mg/L	0.1 mg/L	0.1 mg/L
	Chloride	N/A	<u>250 mg/L</u>	N/A	N/A	N/A	250 mg/L
	Chlorine	N/A	N/A	<u>0.002 mg/L</u>	N/A	N/A	N/A
	Cobalt	N/A	N/A	<u>0.0009 mg/L</u>	N/A	N/A	N/A
	Copper	N/A	<u>1 mg/L</u>	0.005 mg/L	1 mg/L	1 mg/L	1.3 mg/L

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Inorganic Chemicals	Cyanide	<u>0.2 mg/L</u>	0.2 mg/L	0.005 mg/L	0.15 mg/L	0.2 mg/L	0.2 mg/L
	Fluoride	<u>1.5 mg/L</u>	1.5 mg/L	N/A	2 mg/L	4 mg/L	4 mg/L
	Iron	N/A	<u>0.3 mg/L</u>	0.3 mg/L	0.3 mg/L	0.3 mg/L	0.3 mg/L
	Lead	<u>0.01 mg/L</u>	0.01 mg/L	Hardness (CaCO ₃ , mg/L) <30, 0.001 mg/L 30-80, 0.003 mg/L >80, 0.005 mg/L	N/A	0.015 mg/L	0.015 mg/L
	Manganese	N/A	<u>0.05 mg/L</u>	N/A	0.05 mg/L	0.05 mg/L	0.05 mg/L
	Mercury	<u>0.001 mg/L</u>	0.001 mg/L	0.0002 mg/L	0.002 mg/L	0.002 mg/L	0.002 mg/L
	Molybdenum	N/A	N/A	<u>0.04 mg/L</u>	N/A	N/A	N/A
	Nickel	N/A	N/A	0.025 mg/L	<u>0.1 mg/L</u>	0.1 mg/L	N/A
	NO ₃ ⁻ -N	<u>10 mg/L</u>	10 mg/L	N/A	NO ₃ ⁻ -N+ NO ₂ ⁻ -N, 10 mg/L	10 mg/L	10 mg/L
	NO ₂ ⁻ -N	<u>1mg/L</u>	1 mg/L	N/A	1 mg/L	1 mg/L	1 mg/L
Perchlorate	N/A	N/A	N/A	<u>0.006 mg/L</u>	N/A	N/A	

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Inorganic Chemicals	Phosphorus, total	N/A	N/A	<u>0.01 mg/L against aesthetic deterioration</u> 0.02 mg/L to avoid algal growth; 0.03 mg/L to avoid plant growth	N/A	N/A	N/A
	Selenium	<u>0.01mg/L</u>	0.01mg/L	0.1 mg/L	0.05 mg/L	0.05mg/L	0.05mg/L
	Thallium	N/A	N/A	N/A	<u>0.002 mg/L</u>	0.002 mg/L	0.002 mg/L
	Zinc	N/A	<u>5 mg/L</u>	0.03 mg/L	5 mg/L	5 mg/L	5 mg/L
Volatile Organic Chemicals	Aldrin+Dieldrin	<u>0.0007 mg/L</u>	N/A	0.000001 mg/L	N/A	N/A	N/A
	Azinphos-methyl	<u>0.02 mg/L</u>	0.02 mg/L	N/A	N/A	N/A	N/A
	Benzene	<u>0.005 mg/L</u>	0.005 mg/L	0.1 mg/L	0.001 mg/L	0.001 mg/L	0.005 mg/L
	Carbon Tetrachloride (CTC)	0.005 mg/L	<u>0.002 mg/L</u>	N/A	0.0005 mg/L	0.003 mg/L	0.005 mg/L
	Chlorpyrifos	<u>0.09 mg/L</u>	0.09 mg/L	0.000001 mg/L	N/A	N/A	N/A
	Dicamba	<u>0.12 mg/L</u>	0.12 mg/L	0.2 mg/L	N/A	N/A	N/A
	1,2-Dichlorobenzene	<u>0.2mg/L</u>	0.2mg/L	0.0025 mg/L	0.6mg/L	N/A	N/A
1,4-Dichlorobenzene	<u>0.005 mg/L</u>	0.005 mg/L	0.004 mg/L	0.005 mg/L	N/A	0.075 mg/L	

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Volatile Organic Chemicals	Dichlorodiphenyl-trichloroethane (DDT) + metabolites	<u>0.03 mg/L</u>	N/A	N/A	N/A	N/A	N/A
	1,1-Dichloroethane	N/A	N/A	0.2 mg/L	<u>0.005 mg/L</u>	N/A	N/A
	1,2-Dichloroethane (1,2-DCA)	<u>0.005 mg/L</u>	0.005 mg/L	0.1 mg/L	0.0005 mg/L	0.003 mg/L	0.005 mg/L
	1,1-Dichloroethene (1,1-DCE)	N/A	N/A	N/A	<u>0.006 mg/L</u>	N/A	N/A
	1,1-Dichloroethylene (vinylidenechloride)	<u>0.014 mg/L</u>	0.014 mg/L	0.04 mg/L	N/A	0.007mg/L	0.007 mg/L
	Cis-1,2-Dichloroethylene	N/A	N/A	0.2 mg/L	<u>0.006 mg/L</u>	0.07 mg/L	0.07 mg/L
	Trans-1,2-Dichloroethylene	N/A	N/A	0.2 mg/L	<u>0.01 mg/L</u>	N/A	0.1 mg/L
	Dichloromethane	<u>0.05 mg/L</u>	0.05 mg/L	N/A	0.005 mg/L	0.005 mg/L	0.005 mg/L
	2,4-Dichlorophenol	<u>0.9 mg/L</u>	0.9 mg/L	0.0002 mg/L	N/A	N/A	N/A
	1,2-Dichloropropane	N/A	N/A	0.0007 mg/L	<u>0.005 mg/L</u>	0.005 mg/L	0.005 mg/L
	1,3-Dichloropropene	N/A	N/A	N/A	<u>0.0005 mg/L</u>	N/A	N/A
	Ethylbenzene	N/A	<u>0.0024 mg/L</u>	0.008 mg/L	0.3 mg/L	0.7 mg/L	0.7 mg/L

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Volatile Organic Chemicals	Methyl-tert-butyl-ether (MTBE)	N/A	<u>0.015 mg/L</u>	0.2 mg/L	0.013 mg/L	N/A	N/A
	Monochlorobenzene	<u>0.08 mg/L</u>	0.08 mg/L	N/A	0.07 mg/L	0.1 mg/L	0.1 mg/L
	N-Nitrosodimethylamine (NDMA)	<u>0.000009 mg/L</u>	0.00004 mg/L	0.015 mg/L	N/A	N/A	N/A
	Phorate	<u>0.002 mg/L</u>	0.002 mg/L	N/A	N/A	N/A	N/A
	Prometryne	<u>0.001 mg/L</u>	N/A	N/A	N/A	N/A	N/A
	Styrene	N/A	N/A	0.004 mg/L	<u>0.1 mg/L</u>	0.1 mg/L	0.1 mg/L
	Terbufos	<u>0.001 mg/L</u>	0.001 mg/L	N/A	N/A	N/A	N/A
	1,1,2,2-Tetrachloroethane	N/A	N/A	0.07 mg/L	<u>0.001 mg/L</u>	N/A	N/A
	Tetrachloroethylene (PCE)	<u>0.03 mg/L</u>	0.03 mg/L	0.05 mg/L	0.005 mg/L	0.003 mg/L	0.005 mg/L
	2,3,4,6-Tetrachlorophenol	<u>0.1 mg/L</u>	0.1 mg/L	0.001 mg/L	N/A	N/A	N/A
	Triallate	<u>0.23 mg/L</u>	N/A	N/A	N/A	N/A	N/A
	1,2,4-Trichlorobenzene	N/A	N/A	0.0005 mg/L	<u>0.005 mg/L</u>	0.07 mg/L	0.07 mg/L
	1,1,1-Trichloroethane	N/A	N/A	0.01 mg/L	<u>0.2 mg/L</u>	0.2 mg/L	0.2 mg/L
	1,1,2-Trichloroethane	N/A	N/A	0.8 mg/L	<u>0.005 mg/L</u>	0.005 mg/L	0.005 mg/L
Trichloroethylene (TCE)	<u>0.005 mg/L</u>	0.005 mg/L	0.02 mg/L	0.005 mg/L	0.003 mg/L	0.005 mg/L	

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Volatile Organic Chemicals	Trichlorofluoromethane	N/A	N/A	N/A	<u>0.15 mg/L</u>	N/A	N/A
	Trifluralin	<u>0.045 mg/L</u>	0.045 mg/L	N/A	N/A	N/A	N/A
	Trihalomethanes (THM)	<u>0.1 mg/L</u>	0.1 mg/L	N/A	N/A	N/A	N/A
	Vinyl Chloride	<u>0.002 mg/L</u>	0.002 mg/L	0.6 mg/L	0.0005 mg/L	0.001 mg/L	0.002 mg/L
	Xylenes (m,p)	N/A	<u>0.3 mg/L</u>	-m, 0.002 mg/L -p, 0.03 mg/L	1.75 mg/L	10 mg/L (Total)	10 mg/L (Total)
Non-Volatile Synthetic Organic Chemicals	Alachlor	<u>0.005 mg/L</u>	N/A	N/A	0.002 mg/L	0.002 mg/L	0.002 mg/L
	Aldicarb	<u>0.009 mg/L</u>	N/A	N/A	N/A	N/A	N/A
	Atrazine	<u>0.005 mg/L</u>	0.005 mg/L	N/A	0.001 mg/L	0.003 mg/L	0.003 mg/L
	Bendiocarb	<u>0.04 mg/L</u>	N/A	N/A	N/A	N/A	N/A
	Bentazon	N/A	N/A	N/A	<u>0.018 mg/L</u>	N/A	N/A
	Benzopyrene	<u>0.00001 mg/L</u>	0.00001 mg/L	N/A	0.0002 mg/L	0.0002 mg/L	0.0002 mg/L
	Bromoxynil	<u>0.005 mg/L</u>	0.005 mg/L	N/A	N/A	N/A	N/A
	Carbaryl	<u>0.09 mg/L</u>	0.09 mg/L	0.0002 mg/L	N/A	N/A	N/A
	Carbofuran	<u>0.09 mg/L</u>	0.09 mg/L	N/A	0.018 mg/L	0.04 mg/L	0.04mg/L
	Chlordane	<u>0.007 mg/L</u>	N/A	0.00006 mg/L	0.0001mg/L	0.002mg/L	0.002mg/L
	Cyanazine	<u>0.01 mg/L</u>	N/A	N/A	N/A	N/A	N/A
Dalapon	N/A	N/A	0.11 mg/L	<u>0.2 mg/L</u>	0.2 mg/L	0.2 mg/L	

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Non-Volatile Synthetic Organic Chemicals	Di(2-ethylhexyl)adipate	N/A	N/A	N/A	<u>0.4 mg/L</u>	0.4 mg/L	N/A
	Di(2-ethylhexyl)phthalate (DEHP)	N/A	N/A	N/A	<u>0.004 mg/L</u>	0.006 mg/L	0.006 mg/L
	Diazinon	<u>0.02 mg/L</u>	0.02 mg/L	0.00008 mg/L	N/A	N/A	N/A
	1,2-Dibromo-3-chloropropane (DBCP)	N/A	N/A	N/A	<u>0.0002 mg/L</u>	N/A	N/A
	2,4-Dichloro-phenoxyacetic Acid (2,4-D)	<u>0.1 mg/L</u>	0.1 mg/L	N/A	0.07 mg/L	0.07 mg/L	0.07 mg/L
	Diclofop-methyl	<u>0.009 mg/L</u>	0.009 mg/L	N/A	N/A	N/A	N/A
	Dimethoate	<u>0.02 mg/L</u>	0.02 mg/L	N/A	N/A	N/A	N/A
	Dinoseb	<u>0.01 mg/L</u>	N/A	N/A	0.007 mg/L	0.007 mg/L	0.007 mg/L
	Dioxin and Furan	<u>0.00000015 mg/L</u>	N/A	N/A	N/A	N/A	N/A
	Diquat	<u>0.07 mg/L</u>	0.07 mg/L	0.0005 mg/L	0.02 mg/L	0.02 mg/L	0.02 mg/L
	Diuron	<u>0.15 mg/L</u>	0.15 mg/L	0.0016 mg/L	N/A	N/A	N/A
	Endothall	N/A	N/A	N/A	<u>0.1 mg/L</u>	0.1 mg/L	0.1 mg/L
	Endrin	N/A	N/A	0.000002 mg/L	<u>0.002 mg/L</u>	0.002 mg/L	0.002 mg/L

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Non-Volatile Synthetic Organic Chemicals	Ethylene Dibromide (EDB)	N/A	N/A	0.005 mg/L	0.00005 mg/L	<u>0.00002 mg/L</u>	0.00005 mg/L
	Glyphosate	<u>0.28 mg/L</u>	0.28 mg/L	N/A	0.7 mg/L	0.7 mg/L	0.7 mg/L
	Hexachlorobenzene	N/A	N/A	0.0000065 mg/L	<u>0.001 mg/L</u>	0.001 mg/L	0.001 mg/L
	Hexachlorocyclopentadiene	N/A	N/A	0.00006 mg/L	<u>0.05 mg/L</u>	0.05 mg/L	0.05 mg/L
	Heptachlor + Heptachlor Epoxide	<u>0.003 mg/L</u>	N/A	0.000001 mg/L	Heptachlor, 0.00001mg/L; Heptachlor Epoxide, 0.00001mg/L	Heptachlor, 0.0004 mg/L; Heptachlor Epoxide, 0.0002 mg/L	Heptachlor, 0.0004 mg/L; Heptachlor Epoxide, 0.0002 mg/L
	Lindane	<u>0.004 mg/L</u>	N/A	0.00001 mg/L	0.0002 mg/L	0.0002 mg/L	0.0002 mg/L
	Malathion	<u>0.19 mg/L</u>	0.19 mg/L	0.0001 mg/L	N/A	N/A	N/A
	Methoxychlor	<u>0.9 mg/L</u>	N/A	0.00004 mg/L	0.03 mg/L	0.04 mg/L	0.04 mg/L
	Metolachlor	<u>0.05 mg/L</u>	0.05 mg/L	N/A	N/A	N/A	N/A
	Metribuzin	<u>0.08 mg/L</u>	0.08 mg/L	N/A	N/A	N/A	N/A
	Microystin-LR	<u>0.0015 mg/L</u>	0.0015 mg/L	N/A	N/A	N/A	N/A
Molinate	N/A	N/A	N/A	<u>0.02 mg/L</u>	N/A	N/A	

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Non-Volatile Synthetic Organic Chemicals	Nitrilotriacetic Acid (NTA)	<u>0.4 mg/L</u>	0.4 mg/L	N/A	N/A	N/A	N/A
	Oxamyl	N/A	N/A	N/A	<u>0.05 mg/L</u>	0.2 mg/L	0.2 mg/L
	Paraquat	<u>0.01 mg/L</u>	Paraquat dichlorite: 0.01 mg/L Paraquat ion: 0.007 mg/L	N/A	N/A	N/A	N/A
	Parathion	<u>0.05 mg/L</u>	N/A	0.000008 mg/L	N/A	N/A	N/A
	Pentachlorophenol	<u>0.06 mg/L</u>	0.06 mg/L	0.0005 mg/L	0.001 mg/L	0.001 mg/L	0.001 mg/L
	Picloram	<u>0.19 mg/L</u>	0.19 mg/L	N/A	0.5 mg/L	0.5 mg/L	0.5 mg/L
	Polychlorinated Biphenyls (PCB)	<u>0.003 mg/L</u>	N/A	0.000001 mg/L	0.0005 mg/L	0.0005 mg/L	0.0005 mg/L
	Simazine	<u>0.01 mg/L</u>	0.01 mg/L	0.01 mg/L	0.004 mg/L	0.004 mg/L	0.004 mg/L
	Temephos	<u>0.28 mg/L</u>	N/A	N/A	N/A	N/A	N/A
	Thiobencarb	N/A	N/A	N/A	<u>0.07 mg/L</u>	N/A	N/A
	Toxaphene	N/A	N/A	0.000008 mg/L	<u>0.003 mg/L</u>	0.003 mg/L	0.003 mg/L
2,3,7,8-TCDD (Dioxin)	N/A	N/A	N/A	<u>3 × 10⁻⁶ mg/L</u>	N/A	N/A	

(To be continued)

Table 4.3 Summary of the Maximum Limits for Microbial and Chemical Parameters for MAR

Parameters		Drinking Water Quality Standards		Ontario Provincial Water Quality Objectives ³	Water Reuse Managed Aquifer Recharge Guidelines for Potable Uses		
		Ontario ¹	Health Canada ²		California ⁴	Florida ⁵	Idaho ⁶
Non-Volatile	2,4,5-TP (Silvex)	N/A	N/A	N/A	<u>0.05 mg/L</u>	N/A	0.05 mg/L
Synthetic	2,4,6-Trichlorophenol	<u>0.005 mg/L</u>	0.005 mg/L	0.018 mg/L	N/A	N/A	N/A
Organic Chemicals	2,4,5-Trichlorophenoxy acetic acid (2, 4, 5-T)	<u>0.28 mg/L</u>	N/A	N/A	N/A	N/A	N/A

Footnote: 7. the calculation is based on the concentrations in raw surface water and in treated drinking water;

8. the calculation is based on the concentrations in raw wastewater and in reclaimed water.

References for the table:

1. Ontario Ministry of the Environment, 2002;
2. Health Canada, 2012d;
3. Ontario Ministry of the Environment, 1994;
4. California Department of Public Health, 2014;
5. Florida Department of State, 1999;
6. Idaho Department of Environmental Quality, 2009

For enteric viruses, a minimum 12 log reduction target is required for the treatment of raw wastewater in California regulation for MAR with reclaimed water. To determine the treatment goal in terms of municipal wastewater effluents, it would be reasonable to deduct the enteric viruses reduction credit for conventional wastewater treatment processes from the California target. Since around 5 log reduction of enteric viruses can be assigned to conventional wastewater treatment processes which include activated sludge treatment, tertiary filtration and disinfection (U.S. EPA, 1983; Payment *et al.*, 1986; Health Canada, 2011), at least 7 log additional reduction for enteric viruses should be achieved for the treatment of effluents to ensure the safety of potable reuse, since not all wastewater plants would have tertiary filtration. For *Giardia* and *Cryptosporidium*, the Health Canada drinking water standard specifies a minimum 3 log reduction target for the treatment of surface water, which normally contains a few to 10 (oo)cysts per liter (U.S.EPA, 2000a; U.S.EPA, 2001). Since the reported levels of *Giardia* and *Cryptosporidium* in treated wastewater effluents are from 10 to 1,000 (oo)cysts per liter (U.S.EPA, 2000a; U.S.EPA, 2001), which are at most 1000 times those in surface water, an additional 3 log reduction of these two types of protozoa are needed for wastewater effluent to reduce the microbial hazards for drinking water purposes. In conclusion, the newly defined treatment goals for these three types of pathogens in wastewater effluents are 7 log reduction for enteric viruses, 6 log reduction for *Giardia* and *Cryptosporidium*.

In terms of chemical parameters, the defined maximum allowable concentrations are also highlighted in Table 4.3. The values are normally set based on Ontario and Health Canada drinking water regulations/guidelines since the ultimate goal for MAR is potable use. Between these two documents, the lowest value is used as the defined limit for each parameter. If contaminants are not regulated in Canadian drinking water rules, the most stringent values chosen from the California, Florida, or Idaho water reuse regulations were used as the water quality limits. Since the Ontario Provincial Water Quality Objectives (PWQO) often specify parameter limits with values much lower than the limits in the Ontario

or Health Canada drinking water documents, or the California, Florida, or Idaho water reuse documents, the PWQO limits may be too stringent for MAR with reclaimed water and may increase the costs and difficulties of water pre-treatment systems. Only contaminants which are not included in the other five regulatory rules were chosen based on PWQO limits. When several limits are specified in PWQO for one substance such as phosphorus, the lowest value is selected as the target to ensure the high quality of water.

4.4 Developing a List of Priority Contaminants for MAR with Reclaimed Water

4.4.1 Selection of Predominant Contaminants

Predominant contaminants are the residual regulated substances in a wastewater effluent for which concentrations are higher than the defined recharge water quality limits for MAR which were discussed in section 4.3. WWTP effluent monitoring data are valuable to understand the condition of wastewater effluent. By comparing the water quality parameters from WWTP monitoring data with the defined regulated targets for MAR, the predominant contaminants can be identified. It is important to identify compounds that are above the target concentration, since these will require further treatment before the water can be used for MAR.

The wastewater effluent monitoring data used in this study were provided by Halton Region, and is based on typical values that can be achieved through a conventional tertiary treatment process as described in Chapter 3. To identify predominant contaminants in WWTP effluents for possible use in MAR, wastewater effluent quality was statistically analyzed using example monitoring data for a 6 year period, and the results are summarized in Table 4.4.

Table 4.4 Summary of WWTP Final Effluent Quality Data

Contaminant Category	Water quality parameters	Number of samples	Number of nondetects	Minimum values (mg/L except as noted)	Maximum values (mg/L except as noted)	Mean values (mg/L except as noted)
Typical reclaimed water quality parameters	Alkalinity	63	0	112	232	178.3
	CBOD	330	223	<1.0	4	N/A ¹
	TSS	330	174	<1.0	6.4	N/A ¹
Microorganisms	<i>E.coli</i>	330	0	0 CFU/100 mL	280 CFU /100 mL	1 CFU /100 mL
Nutrients	NO3--N	329	0	9.43	27.9	18.0
	NO2--N	329	0	0.01	2.03	0.2
	Total Ammonia (as nitrogen)	332	130	<0.02	4.51	0.44
	Total Kjeldahl Nitrogen	328	0	0.7	4.9	1.4
	Ortho-Phosphates	88	30	<0.02	0.44	0.05
	Total Phosphorus	331	0	0.03	0.59	0.11
	Unionized Ammonia (ECA ²)	332	216	0.001	0.027	N/A ¹
	Unionized Ammonia (WSER ³)	69	50	<0.001	0.01	N/A ¹
	Aluminum	75	0	0.068	0.724	0.198
	Antimony	75	73	<0.0005	0.0013	N/A ¹
	Arsenic	82	70	<0.0004	0.0012	N/A ¹
	Cadmium	75	12	<0.0001	0.0041	0.0012
	Chromium	75	5	0.0005	0.002	0.0011
	Cobalt	75	28	<0.0002	0.0008	0.0004
	Copper	75	0	0.004	0.019	0.011
	Iron	73	0	0.013	0.0659	0.026
	Lead	75	74	<0.0005	0.007	N/A ¹
	Manganese	75	0	0.0084	0.105	0.0412
	Molybdenum	75	0	0.0008	0.0178	0.0055
	Nickel	75	0	0.0003	0.0333	0.0027
Selenium	75	70	<0.0005	0.0007	N/A ¹	
Zinc	75	0	0.003	0.0462	0.003	

(To be continued)

Table 4.4 Summary of WWTP Final Effluent Quality Data

Contaminant Category	Water quality parameters	Number of samples	Number of nondetects	Minimum values (mg/L except as noted)	Maximum values (mg/L except as noted)	Mean values (mg/L except as noted)
Salts	Chloride	55	0	247	388	297

1. The calculation of mean value is not available since there are more than 50% nondetects.
2. Unionized Ammonia is tested based on the method in Environmental Compliant Approval (MOE, 2007).
3. Unionized Ammonia is tested based on the method in Wastewater Systems Effluent Regulations (Government of Canada, 2014).

From Table 4.4, it can be seen that some parameters' monitoring data contain values below the detection limits. However, determining whether the contaminant concentrations in wastewater effluent are in compliance with the regulated values is usually judged by comparing maximum and mean values of monitoring data with the water quality targets. To calculate the mean values, nondetects were handled by following the methods described in the U.S. EPA *Guidance for Data Quality Assessment* (US EPA, 2000), shown in Table 4.5.

Table 4.5 Methods to Analyze Nondetects in a Data Set

Percentage of Nondetects	Statistical Analysis Method
<15%	Substitute nondetects with half of the detection limit
15%-50%	Develop a Winsorized Mean. Replace data in the tails of a data set with the next most extreme data value. (A detailed description of the method is provided in Appendix A)
>50%-90%	The calculation of mean values cannot be done. Instead, a different value (i.e. percentile) should be used.

In keeping with the information in Table 4.5, the selection of an appropriate method to analyze data containing nondetects depends on the percentage of nondetects in the data set. When less than 15% of observations are under the detection limit, these nondetects are usually replaced with half of the detection limit. When 15% to 50% of observations are below the detection limits, there are four possible methods described, including Aitchison's method, Cohen's method, Trimmed mean method, and Winsorized mean method (U.S.EPA, 2000).

The Aitchison's method assumes that nondetects are actually zero, and therefore this method does not apply to the WWTP monitoring data. Cohen's method assumes that the data set without the nondetects is normally distributed. However, the WWTP effluent monitoring data were assessed using distribution fitting and results (not shown in the thesis) showed that the data were not normally distributed, which is the normal condition for environmental data such as wastewater effluent monitoring data (Helsel, 1990). Therefore, Cohen's method was also not applicable. The trimmed mean method discards data in the tails of a data set to develop an unbiased estimate of the population mean. However, the trimmed mean is not a good estimator of skewed (non-symmetric) data, and therefore this method was also not applicable. The Winsorized Mean method replaces the tails of a data set with the next most extreme data value. This approach can provide a nearly unbiased estimator of the mean for skewed data (Rivest, 1994), which is the case for the wastewater effluent data sets. Therefore, this method was used when the percentage of nondetects is between 15% to 50%. The Winsorized Mean method is explained in more detail in Appendix A, and includes an example calculation. When more than 50% of observations are below the detection limit, there is no method available or recommended for calculation of mean values (U.S.EPA, 2000). In this case, data should instead be evaluated using a different approach such as percentiles. For example, if 70% of the data are below the detection limit, the 75th percentile of data instead of the mean value could be considered as the value to be compared with the water quality limit.

According to Table 4.4, the WWTP data set contains 27 parameters for wastewater effluent. In terms of typical reclaimed water quality parameters, alkalinity, CBOD, and TSS were included. These values were compared with the limits defined earlier in Table 4.2. The final identified predominant contaminant list of compounds that require further treatment, based on the WWTP effluent monitoring data, is shown in Table 4.6. Although alkalinity is not included in the defined water quality target list, its maximum monitoring value falls within the range of most natural water's, which is from 10 to 500 mg/L (U.S. Department of the Interior Bureau of Reclamation, 2009). CBOD was typically below the detection limit of 1 mg/L and the maximum monitoring value (4 mg/L) was less than the defined limits of 2 mg/L

(monthly average) and 5 mg/L (maximum value) from Table 4.2, therefore the wastewater effluent CBOD doesn't need to be further treated. However, the maximum value of TSS (6.4 mg/L) is larger than the defined maximum limit of 5 mg/L; therefore, TSS in the wastewater effluent should be further removed. For microorganisms, only *E.coli* was monitored. Since the maximum concentration of *E.coli* was 280 CFU/100 mL, which exceeds the defined limit of none detectable/100 mL, further treatment will be required to reduce microorganisms in the wastewater effluent.

Table 4.6 Identified Predominant Contaminants

Contaminant category	Parameters	Monitoring values	Defined water quality targets
Microorganisms	<i>E.coli</i>	0-280 CFU/100 mL (n=330), Mean=1 CFU/100 mL	None detectable /100 mL
Nutrients	Nitrite Nitrogen	0.01-2.03 mg/L (n=329), Mean=0.2 mg/L	1 mg/L (max)
	Nitrate Nitrogen	9.43-27.9 mg/L (n=329), Mean=18.0 mg/L	10 mg/L (max)
	Total Ammonia Nitrogen	0.03-4.51 mg/L (n=332), Mean=0.44 mg/L	0.024 mg/L (max)
Nutrients	Total Phosphorus	0.03-0.59 mg/L (n=331), Mean=0.11 mg/L	0.01 mg/L (max)
Metals	Aluminum	0.068-0.724 mg/L (n=75), Mean=0.198 mg/L	0.1 mg/L (max)
	Manganese	0.0008-0.105 mg/L (n=75), Mean=0.0412 mg/L	0.05 mg/L (max)
Salts	Chloride	247-388 mg/L (n=330), Mean=297 mg/L	250 mg/L (max)

max: maximum value of monitoring data should be smaller than the limit

For nutrients, seven parameters, including nitrate, nitrite, total ammonia, unionized ammonia, total Kjeldahl nitrogen, ortho-phosphates, and total phosphorus, were monitored. However, only nitrate, nitrite, total ammonia, and total phosphorus have specified limits in the drinking water/MAR documents (Table 4.3). Since the maximum monitoring values of each parameter

was greater than the defined MAR limits, the nitrogen and phosphorus levels in the wastewater effluent should be further reduced. In addition, data for 14 metal ions was provided, but only aluminum and manganese have higher maximum values than the defined MAR limits. Hence, these two metals are identified as the predominant contaminants that require further treatment. For salts, the chloride maximum concentration reaches 388 mg/L, which is higher than the defined MAR limit (250 mg/L). Although chloride is included in the Health Canada and Idaho guidelines as an aesthetic objective, appropriate treatments should be used to lower the chloride concentration in wastewater effluent.

4.4.2 Selection of Potential Additional Contaminants

Since WWTPs do not routinely monitor for specific types of organic contaminants in wastewater effluent, the concentrations of organics are unknown. However, organic compounds are an important type of contaminant for potable reuse. In addition, there are a number of additional pathogens/indicator groups that are not measured in wastewater effluents, but can be used to assess overall health risk. Therefore, potential organic contaminants and microorganisms which have a high possibility to exist in the effluent should be assessed. This was done by conducting a literature survey to determine concentrations that are typical in wastewater treatment plant effluent that have treatment systems similar to the one used in this study.

The defined regulated organic contaminant list (Table 4.3) can serve as the basis for the selection, since the organics included in the list have been recognized as the best indicators for water quality based on the exposure and adverse health effects (Health Canada, 2012d). According to the type and application of chemicals, the listed organics can be classified into groups. According to Table 4.3, regulated organics have two main groups: volatile organics and non-volatile organics. Since conventional wastewater treatments can serve as a gas stripping process to remove volatile organics, their concentrations are very low and normally below the guideline values (Nikolaou *et al.*, 2002; Barco-Bonilla *et al.*, 2011).

Therefore, volatile organics are considered as lower priority contaminants and can be removed from considerations as potential contaminants. Non-volatile organics can be classified into six groups, which are herbicides/pesticides, plasticizers, polycyclic aromatic hydrocarbons (PAHs), industrial products/by-products, cyanotoxins, detergents (Table 4.7). Herbicides/pesticides is the main contaminant group in the list and contains 45 organics, accounting for 88% of chemicals regulated. The other five groups contain fewer compounds (1 or 2 chemicals in each group).

Table 4.7 Classification of Regulated Non-volatile Organics

Contaminant group	Regulated contaminant
Herbicide/pesticide	Alachlor, Aldicarb, Atrazine, Bendiocarb, Bentazon, Bromoxynil, Carbaryl, Carbofuran, Chlordane, Cyanazine, Dalapon, Diazinon, 1,2-Dibromo-3-chloropropane (DBCP), Diclofop-methyl, Dinoseb, 2,4-Dichloro-phenoxyacetic Acid (2,4-D), Dimethoate, Diquate, Diruron, Endothall, Endrin, Ethylene Dibromide (EDB), Lindane, Glyphosate, Heptachlor+Heptachlor Epoxide, Hexachlorobenzene, Hexachlorocyclopentadiene, Malathion, Methoxychlor, Metribuzin, Metolachlor, Molinate, Oxamyl, Paraquat, Parathion, Thiobencarb, Pentachlorophenol, Picloram, Simazine, Temephos, Toxaphene, 2,3,7,8-TCDD (Dioxin), 2,4,5-TP (Silvex), 2,4,6-Trichlorophenol, 2,4,5-Trichlorophenoxy acetic acid (2,4,5-T)
Plasticizer	Di(2-ethylhexyl)adipate, Di(2-ethylhexyl)phthalate (DEHP)
Polycyclic aromatic hydrocarbons (PAHs)	Benzopyrene
Industrial products/by-products	Dioxin and Furan, Polychlorinated Biphenyle (PCB)
Cyanotoxins	Microcystin-LR
Detergent	Nitrilotriacetic Acid (NTA)

Since the number of non-volatile organics is large, it is not efficient to regard all the organics in Table 4.7 as treatment targets and analyze the treatment alternatives to remove them. Therefore, a list of priority contaminants which are expected to have high concentrations in wastewater effluents should be developed. The chemicals which are most frequently used and resistant to conventional wastewater treatments are expected to have high concentrations in wastewater effluent, and hence can be considered as representatives for

certain chemical groups. The representative selection was mainly based on the occurrences and concentrations of chemicals in wastewater effluent from published studies.

For the PAHs group, only one chemical (benzopyrene) is regulated. However, this chemical has low solubility in water and often binds to particulate matter, which can be removed by the filtration process (U.S. EPA, 2007). Since the wastewater treatment process used in this case study includes tertiary filtration, this chemical will have a lower possibility to exist in the wastewater effluent and can be deleted from the potential contaminant list. The industrial products/by-products group can also be removed since this study assumed that the WWTP would not receive industrial waste that would contain this type of chemical. However, the inclusion of industrial products will be very site specific, and in other cases where wastewater treatment plants have known inputs from industry, specific chemicals in this group would need to be included. Cyanotoxins are produced by cyanobacteria, which are found to seldom appear in wastewater. Therefore, this type of chemical does not need to be further treated.

Since the herbicides/pesticides group contains the greatest number of regulated organics, several chemicals should be selected to represent different classes of compounds. Two chemicals which have different chemical structures, atrazine and diuron, were identified as representatives due to their high extent of use in agriculture and resistance to conventional wastewater treatment processes (Martínez Bueno *et al.*, 2012; Köck-Schulmeyer *et al.*, 2013; Alidina *et al.*, 2014; James *et al.*, 2014; Luo *et al.*, 2014). Because there were no data provided on these compounds for the WWTP effluent, concentrations found in WWTP effluents were obtained from the literature (Wintgens *et al.*, 2008; Wert *et al.*, 2009; Klammerth *et al.*, 2010; Ruel *et al.*, 2010; Prieto-Rodriguez *et al.*, 2012; Campo *et al.*, 2013; Köck-Schulmeyer *et al.*, 2013; Loos *et al.*, 2013). The highest concentrations in municipal wastewater effluents are 0.006 mg/L for atrazine (Wert *et al.*, 2009) and 0.153 mg/L for diuron (Klammerth *et al.*, 2010). Both of these concentrations are higher than the regulated limits.

For plasticizers, DEHP is a widely used substance, which has been frequently detected in municipal wastewater (Fromme *et al.*, 2002; Vethaak *et al.*, 2005; Vogelsang *et al.*, 2006; Yu and Chu, 2009; Clara *et al.*, 2010; Gao *et al.*, 2014; Zolfaghari *et al.*, 2014). Therefore, DEHP was selected, and the highest concentration found in WWTP effluent was 0.182 mg/L (Fromme *et al.*, 2002). For detergents, only one chemical, NTA, was regulated. Due to its extensive usage, NTA was often found in secondary or tertiary effluents of municipal WWTP, ranging from 0.005 to 0.41 mg/L (Alder *et al.*, 1990; Welker, 2007; Conn *et al.*, 2010; Schaar *et al.*, 2010; Clara *et al.*, 2012). Hence, NTA was recognized as the representative for this group.

In terms of microorganisms, *Giardia* cysts and *Cryptosporidium* oocysts were selected as potential microbial contaminants. Although the wastewater treatment system used in this study included UV disinfection, which is reported to be effective to inactivate both parasites (Hijnen *et al.*, 2006), these pathogens may not be completely removed from the wastewater effluent. Some studies which are using UV to disinfect wastewater found that low levels of *Giardia* and *Cryptosporidium* were still detected in final effluent, with a concentration range from 20 to 1100 per liter for *Giardia* and from 1 to 160 per liter for *Cryptosporidium* (Liberti and Notarnicola, 1999; Liberti *et al.*, 2002; Gennarcaro *et al.*, 2003; Neto *et al.*, 2006). Although a maximum acceptable concentration for these pathogens cannot be determined due to the lack of accurate detection methods, the residual *Giardia* cysts and *Cryptosporidium* oocysts in the wastewater effluent may cause the risk of illness (Health Canada, 2009). Therefore, these two pathogens should be considered for removal, which needs to achieve a 6 log reduction through treatment as defined in the earlier section 4.3. Although total coliforms limits are included in the regulations, this microbial parameter cannot provide any direct information about the health risk of water quality but is often used as the operational tool to assess the efficiency of a water treatment system (Health Canada, 2012c). Therefore, this microbial indicator was not selected. Another type of microorganism, enteric viruses, was also not selected for evaluation since their detection methods are not

practical for routine monitoring (Deere *et al.*, 2001; WHO, 2004), and as a result there is little information on their concentration in wastewater effluents. However, viruses will be an important consideration for MAR that should be further investigated in future research studies.

Table 4.8 summarizes the potential microbial and organic contaminants, which are usually not monitored in WWTP effluents, but may have a high possibility to exist in the wastewater effluent and need to be further treated.

Table 4.8 Potential Microbial and Organic Contaminants

Contaminant category		Representative	Values measured in municipal WWTP effluents	Defined water quality targets	References
Microorganisms		<i>Giardia</i>	20-1100 N/L	6 log reduction	1, 2, 3
		<i>Cryptosporidium</i>	1-160 N/L	6 log reduction	1, 2, 3, 4
Organics	Pesticides	Atrazine	0.00004-0.0056 mg/L	0.005 mg/L	5, 6, 7, 8, 9, 10, 11, 12
		Diuron	0.00002-0.153 mg/L	0.15 mg/L	5, 6, 8, 10, 11
	Plasticizers	Di(2-ethylhexyl)phthalate (DEHP)	0.083×10^{-6} -0.182 mg/L	0.004 mg/L	13, 14, 15, 16, 17, 18
	Detergents	Nitritotriacetic Acid (NTA)	0.005-0.41 mg/L	0.4 mg/L	19, 20, 21, 22, 23

1. Liberti and Notarnicola, 1999; 2. Liberti *et al.*, 2002; 3. Neto *et al.*, 2006; 4. Gennacarro *et al.*, 2006;
5. Campo *et al.*, 2013; 6. Loos *et al.*, 2013; 7. Ruel *et al.*, 2010; 8. Köck-Schulmeyer *et al.*, 2013;
9. Prieto-Rodriguez *et al.*, 2012; 10. Klammerth *et al.*, 2010; 11. Wert *et al.*, 2009; 12. Wintgens *et al.*, 2008;
13. Clara *et al.*, 2010; 14. Gao *et al.*, 2014; 15. Yu and Chu, 2009; 16. Vogelsang *et al.*, 2006;
17. Vethaak *et al.*, 2005; 18. Fromme *et al.*, 2002; 19. Clara *et al.*, 2012; 20. Alder *et al.*, 1990;
21. Welker, 2007; 22. Conn *et al.*, 2010; 23. Schaar *et al.*, 2010

4.4.3 Selection of Potential Emerging Contaminants

WWTP effluents are regarded as an important source for emerging contaminants, which are not regulated but may produce adverse ecological and human health effects (Bolong *et al.*, 2009). The emerging contaminants include four main categories: perfluorochemicals (PFCs), pharmaceuticals, antibiotics, and personal care products (da Silva *et al.*, 2013; Li *et al.*, 2014).

Similar to the organic chemicals discussed above in section 4.4.2, no case study data were available on the concentrations of emerging compounds in WWTP effluents. Therefore, potential compounds and their concentrations in WWTP effluents were obtained from the literature. Since there are a large number of emerging contaminants, it is not feasible to regard all of them as the target contaminants. According to their consumption volumes, bioaccumulation, ecological and health effects, and occurrences in wastewater effluent from published studies, important chemicals were selected as the representatives for each group and summarized in Table 4.9.

Table 4.9 Potential Emerging Contaminants

Contaminant category	Representative	Values measured in municipal WWTP effluents	Suggested water quality limits	References
Perfluorochemicals (PFCs)	Perfluorooctane Sulfonate (PFOS)	0.0018-0.462 µg/L	0.2 µg/L ²⁷	1, 2, 3, 4, 5, 6, 7
	Perfluorooctanoate (PFOA)	0.058-1.05µg/L	0.4 µg/L ²⁷	1, 2, 3, 4, 5, 6, 7
Pharmaceuticals	Ibuprofen	0.005 -8.2 µg/L	0.039 µg/L ²⁸	8, 9, 10, 11, 12, 13
	Carbamazepine	0.005-4.6 µg/L	0.61 µg/L ²⁸	8, 12, 13, 15, 24, 25
	Diclofenac	0.001-0.69 µg/L	0.1 µg/L ²⁹	8, 12, 13, 15, 24, 26
Antibiotics	Erythromycin	0.0027 -2.841 µg/L	0.145 µg/L ³⁰	9, 12, 14, 15, 16
	Sulfamethoxazol	0.003-1.15 µg/L	0.025 µg/L ²⁸	8, 12, 13, 14, 24, 26
Personal care products	Nonylphenol	0.1 -7.8 µg/L	0.7 µg/L ³¹	17, 18, 19, 20, 21, 22, 23

Footnote: 28. The suggested water quality limits are based on Kormos, 2009;

30. The suggested water quality limits are based on Kleywegt *et al.*, 2011.

References for the table:

1. Boulanger *et al.*, 2005; 2. Sinclair and Kannan, 2006; 3. Loganathan *et al.*, 2007; 4. Becker *et al.*, 2008;
5. Bossi *et al.*, 2008; 6. Plumlee *et al.*, 2008; 7. Yu *et al.*, 2009; 8. Loos *et al.*, 2013;
9. Prieto-Rodriguez *et al.*, 2012; 10. Wert *et al.*, 2009; 11. Yu and Chu, 2009; 12. Kasprzyk-Hordern *et al.*, 2009;
13. Santos *et al.*, 2009; 14. Gracia-Lor *et al.*, 2012; 15. Zhou *et al.*, 2010; 16. Pasquini *et al.*, 2014;
17. Ruel *et al.*, 2010; 18. Vogelsang *et al.*, 2006; 19. Vethaak *et al.*, 2005; 20. Céspedes *et al.*, 2008;
21. Janex-Habibi *et al.*, 2009; 22. Nie *et al.*, 2012; 23. Pothitou and Voutsas, 2008; 24. Behera *et al.*, 2011;
25. Singer *et al.*, 2010; 26. Terzi *et al.*, 2008; 27. U.S.EPA, 2009; 28. Kormos, 2007; 29. European Union, 2011;
30. Kleywegt *et al.*, 2011; 31. Environment Canada, 2002

For PFCs group, PFOS and PFOA are commonly detected perfluorochemicals in aquatic environments (Plumlee *et al.*, 2008). Bioaccumulation of these two chemicals has been reported in different mammals (Sinclair and Kannan, 2006). Due to their poor biodegradability (Pasquini *et al.*, 2014), PFOS and PFOA are persistent in wastewater treatments (Boulanger *et al.*, 2005; Sinclair and Kannan, 2006; Loganathan *et al.*, 2007; Becker *et al.*, 2008; Bossi *et al.*, 2008; Plumlee *et al.*, 2008; Yu *et al.*, 2009) and their concentrations can reach up to 0.462 µg/L (PFOS) and 1.05µg/L (PFOA) in municipal WWTP effluents (Yu *et al.*, 2009). Since provisional advisory values developed by U.S.EPA for these two chemicals are 0.2 µg/L (PFOS) and 0.4µg/L (PFOA), they should be considered for further treatment (U.S.EPA, 2009).

For the pharmaceuticals group, ibuprofen, carbamazepine, and diclofenac have a high consumption volume (Bound and Voulvoulis, 2006; Zhang *et al.*, 2008). Since carbamazepine and diclofenac are poorly removed by WWTPs, they are the most frequently detected pharmaceuticals in wastewater effluents (Terzi *et al.*, 2008; Kasprzyk-Hordern *et al.*, 2009; Santos *et al.*, 2009; Singer *et al.*, 2010; Zhou *et al.*, 2010; Behera *et al.*, 2011; Loos *et al.*, 2013), with the highest concentrations of 4.6 µg/L (carbamazepine) (Kasprzyk-Hordern *et al.*, 2009) and 0.69 µg/L (diclofenac) (Terzi *et al.*, 2008). Although ibuprofen can be biodegraded in WWTPs, due to its high concentration in raw wastewater (Kruglova *et al.*, 2014), this chemical is still ubiquitous in wastewater effluents (Kasprzyk-Hordern *et al.*, 2009; Santos *et al.*, 2009; Wert *et al.*, 2009; Yu and Chu, 2009; Prieto-Rodriguez *et al.*, 2012; Loos *et al.*, 2013) and the highest concentration can reach 8.2 µg/L (Santos *et al.*, 2009). In addition, ibuprofen, carbamazepine, and diclofenac have shown toxic effects on fish, crustaceans, algae, and bacteria even in low concentrations (Ferrari *et al.*, 2003; Nassef *et al.*, 2010; Lee *et al.*, 2011; Zhang *et al.*, 2012). Since the suggested environmental quality standard for diclofenac set by European Commission is 0.1 µg/L (European Union, 2011), the concentrations of this pharmaceutical in wastewater effluents are still relatively high and needs to be reduced to ensure the safety of indirect potable reuse. For ibuprofen and carbamazepine, there are no

recommended limits, but their reported concentrations are 0.039 µg/L for ibuprofen and 0.61µg/L for carbamazepine have been measured in southern Ontario drinking water supplies (Kormos, 2007). In the absence of other information, the values reported by Kormos (2007) are used as the suggested water quality limits. Based on the reported concentrations of ibuprofen and carbamazepine in wastewater effluents, these two pharmaceuticals may have a high possibility to exceed the limits and contaminate water sources and therefore need to be treated.

For antibiotics, erythromycin and sulfamethoxazol are the mostly commonly used medicines against some Gram-positive and Gram-negative bacteria (Alighardashi *et al.*, 2009; Larcher and Yargeau, 2012). They are quite persistent in wastewater effluents (Terzi *et al.*, 2008; Kasprzyk-Hordern *et al.*, 2009; Santos *et al.*, 2009; Zhou *et al.*, 2010; Behera *et al.*, 2011; Gracia-Lor *et al.*, 2012; Prieto-Rodriguez *et al.*, 2012; Loos *et al.*, 2013; Pasquini *et al.*, 2014) with concentrations up to 2.841 µg/L for erythromycin (Kasprzyk-Hordern *et al.*, 2009) and 1.15 µg/L for sulfamethoxazol (Terzi *et al.*, 2008). No recommended limits for these two antibiotics were proposed. However, it was reported that the normal concentrations of erythromycin and sulfamathoxazol in Ontario drinking sources are respectively 0.145µg/L (Kleywegt *et al.*, 2011) and 0.025 µg/L (Kormos, 2007), and therefore these values are used in the present study as the suggested water quality limits. To protect the groundwater quality, these chemicals should be further treated before the highly treated wastewater effluent is recharged into aquifers.

For personal care products, nonylphenol is a compound used for the production of lubricating oil additives and antioxidants, but its major use is for the production of nonylphenol ethoxylates surfactants (U.S.EPA, 1990). Due to the large usage of nonylphenol ethoxylates, which finally arrive at WWTPs and incompletely degrade into nonylphenol (Ahel *et al.*, 1994), substantial amounts of nonylphenol can be detected in wastewater effluents (Vethaak *et al.*, 2005; Vogelsang *et al.*, 2006; Céspedes *et al.*, 2008; Pothitou and Voutsas, 2008; Janex-Habibi *et al.*, 2009; Ruel *et al.*, 2010; Nie *et al.*, 2012), with the highest

concentration of being reported as 7.8 µg/L (Janex-Habibi *et al.*, 2009). Since it has toxicity effects on aquatic life and has been set with an environmental limit of 0.7µg/L (Environment Canada, 2002), additional treatment that would remove nonylphenol should be considered in wastewater reclamation.

4.5 Conclusions

The identification of critical contaminants for MAR with reclaimed water is important for MAR implementation. However, the lack of MAR regulatory documents in Ontario and the absence of monitoring data for specific types of contaminants in WWTP effluents increase the difficulties of this task. To solve the problem, a list of recharge water parameter limits for MAR was defined and an approach to select critical contaminants for MAR was developed. Predominant contaminants, potential microbial and organic contaminants, and potential emerging contaminants, which together comprise critical contaminants for MAR with reclaimed water, were determined based on typical WWTP effluent monitoring data and literature data. A WWTP system and effluent monitoring data were used as a specific example for the purpose of this study, but the same approach could be applied to any municipality considering MAR for potable water use. According to the results of this study, the following conclusions can be drawn:

- Recharge water quality targets for MAR can be defined based on drinking water regulations and guidelines, environmental water quality standards, and worldwide water reuse regulations/guidelines which specify requirements for MAR.
- Statistical analysis of WWTP effluent monitoring data can facilitate the selection of predominant contaminants.
- Potential and emerging microbial and organic chemicals can be studied by selecting representatives from contaminants which have a high probability to exist in wastewater effluents.
- Literature data can be useful in identifying contaminant concentrations for which wastewater effluent data are not available.

Chapter 5

Selection and Evaluation of Water Pre-treatment Technologies for MAR with Reclaimed Water

5.1 Introduction

With the increase of water demands and the lack of fresh water resources, reclaimed water has drawn more attention as an alternative potable water source. To supplement water supply, highly treated wastewater can be recharged into aquifers via surface spreading or direct injection for indirect potable reuse. Although managed aquifer recharge (MAR) can provide a natural system to remove some microbial and chemical contaminants from wastewater (Schmidt *et al.*, 2007; Maeng *et al.*, 2011), some pathogens and trace chemicals may persist in the reclaimed water and cause adverse impacts on the groundwater quality and potential health risks for humans (Asano and Cotruvo, 2004). Therefore, adequate water pre-treatment is needed for MAR with reclaimed water. To remove a wide range of chemical and microbial contaminants, diverse water treatment technologies, ranging from conventional wastewater or drinking water treatments to advanced treatments, have been applied in this field (Gerrity *et al.*, 2013).

Conventional wastewater treatments, especially tertiary treatments, can effectively remove microbial pathogens, large particles, most dissolved organic matter, and some nutrients and inorganic compounds (U.S. EPA, 2012; Gerrity *et al.*, 2013). To achieve a higher level of water quality through wastewater treatment, treatment modifications including increased solid retention time (SRT) and addition of microbial and chemical substances, have been made to further remove nitrogen, phosphorus, and trace organics.

Drinking water treatment can also play an important role in potable reuse applications. As a cost-competitive treatment option, coagulation and flocculation are often used in water

reclamation processes to remove trace organics, and can be quite effective under optimized conditions (Huerta-Fontela *et al.*, 2008; Suarez *et al.*, 2009; Serrano *et al.*, 2010; Huerta-Fontela *et al.*, 2011). Additionally, the application of a coagulation process combined with an advanced treatment process has been found to improve the overall efficiency of trace organics removal (Ternes *et al.*, 2002; Bundy *et al.*, 2007; Huerta-Fontela *et al.*, 2008). Slow granular filtration (SGF) has also shown good performance in removing prevalent contaminants in wastewater effluent, including pathogens, suspended particulates, nutrients, and trace organics. Important mechanisms in SGF for water reuse include enhanced biological activities on the media surface, mechanical ripening, adsorption, and surface catalyzed degradation (Adin, 2003). These SGF processes can also be applied to produce high quality reclaimed water (Adin, 2003; Aslan and Cakici, 2007).

In addition, advanced treatment processes are widely applied in water reclamation due to their high treatment performance. Advanced oxidation process (AOPs) generate hydroxyl radicals and other strong oxidant species to remove trace organics with high chemical stability from wastewater effluent (Andreozzi *et al.*, 1999; Rosal *et al.*, 2008). Due to their effectiveness in removing effluent organic matter (EfOM), AOP technologies have been extensively studied and utilized in wastewater reuse (Rosal *et al.*, 2008; Rosario-Ortiz *et al.*, 2010; Agulló-Barceló *et al.*, 2013; Bierbaum *et al.*, 2014). Granular activated carbon (GAC) and powdered activated carbon (PAC) can also be used to remove soluble organic and inorganic contaminants which are not effectively removed by conventional wastewater treatments (Shon and Vigneswaran, 2006). A number of previous studies have shown that GAC and PAC can effectively remove residual soluble substances in wastewater (Liu *et al.*, 2005; Kazner *et al.*, 2008; Hatt *et al.*, 2013). High pressure membrane filtration, including nanofiltration (NF) and reverse osmosis (RO), is another technology that can effectively remove trace organics from wastewater. This technology has demonstrated its ability to reclaim wastewater in many studies (Alturki *et al.*, 2010; Fujioka *et al.*, 2013; Liu *et al.*, 2013b; Kim *et al.*, 2014). Filtration processes including membrane filtration are also effective

for pathogen removal. Other advanced technologies for pathogen inactivation include UV irradiation and ozonation.

Due to the wide spectrum of treatment technologies that are available, it is important to select and evaluate an appropriate water treatment train for the removal of specific contaminants in wastewater. To ensure that reclaimed water has a final water quality suitable for potable use, this chapter will select water pre-treatment technologies to remove critical contaminants identified in the Chapter 4, and evaluate the treatment performance. A preliminary cost evaluation will be done. The results of this study will then suggest a feasible water treatment scenario for MAR in using reclaimed water. The initial evaluation given in this chapter would provide the basis for more detailed investigations that would be required should a decision be made to go ahead with MAR.

5.2 Treatment Technologies Based on Categories of Critical Contaminants

According to Chapter 4, 22 critical contaminants for MAR with reclaimed water were identified that would require further treatment to meet potable water standards. Since critical contaminants can be grouped together based on similar characteristics, potential water treatment technologies can be proposed initially based on the contaminant group (Table 5.1) Reducing pathogens is a major requirement for water reclamation and reuse since these microorganisms can cause immediate adverse health risks. Chemical (chlorine, chlorine dioxide, chloramine, ozone) and ultraviolet disinfection, granular and membrane filtration, and soil aquifer (filtration/adsorption) treatment are the most frequently used technologies applied for the elimination of pathogens in recharge water.

The second category identified in Table 5.1 includes nitrogen and phosphorus nutrient, which are a focus of wastewater treatment and have been substantially reduced in wastewater effluents. However, residual nutrients in the effluent may not achieve the potable

water standards and cause aesthetic and potential health problems (Ontario Ministry of the Environment, 1994; Health Canada, 2012c). To remove nutrients, ion exchange, membrane filtration, electro dialysis, and chemical reduction are often utilized.

Table 5.1 Potential Water Treatment Technologies for Critical Contaminants

Contaminant groups	Critical contaminants	Proposed water treatment
Pathogens	<i>E.coli, Giardia, Cryptosporidium</i>	Disinfection (chemical, ultraviolet), filtration (membrane, granular), soil aquifer treatment
Nutrients (N, P)	Nitrate, nitrite, total ammonia, total phosphorus,	Ion exchange, membrane filtration, electro dialysis, chemical reduction
Metals	Aluminum, manganese	Ion exchange, membrane filtration, chemical reduction, oxidation, electro dialysis, adsorption
Salts	Chloride	Reverse osmosis, adsorption
Trace organics	Atrazine, diuron, carbamazepine, nitrotriacetic acid (NTA), diclofenac di(2-ethylhexyl)phthalate (DEHP), perfluorooctane sulfonate (PFOS), perfluorooctanoate (PFOA) ibuprofen, erythromycin, nonylphenol	Drinking water treatments, adsorption, ozonation, advanced oxidation processes, membrane filtration

The third and fourth categories respectively include metals and salts. Some metals such as lead and mercury can undergo bio-accumulation in the food chain and are considered as a potential health threat in reclaimed water (Norton-Brandão *et al.*, 2013). However, other metals, including iron and manganese, are mainly regulated because they can cause negative taste and visual effects in water (Tekerlekopoulou and Vayenas, 2007), and it was reported that manganese may be toxic to the central nervous system (Marienfeld and Collins, 1981). Treatment technologies for metal removal include ion exchange, membrane filtration, chemical reduction, oxidation, electro dialysis, and adsorption. For salts, including sodium and chloride ions, there are no health-based standards but only aesthetic concerns for chloride, which can cause a salty taste in drinking water when its concentration reaches 250 mg/L (U.S.EPA, 2013). Ways to treat salts are reverse osmosis and possibly adsorption.

The last category includes trace organics, including compounds that have known health effects (e.g. certain pesticides, herbicides), and also potential emerging contaminants (e.g. pharmaceuticals, personal care products) that have no proven health effects. Since trace organics in wastewater can include known or potential carcinogens and have potential negative impacts on humans' endocrine systems (Jin *et al.*, 2013), this type of chemical will receive more attention in the investigation. Drinking water treatments including coagulation and granular filtration, adsorption, ozonation, AOPs, and membrane filtration, are often used to remove these chemicals.

5.3 Removal Efficiency of Critical Contaminants by Treatment Alternatives

Although the contaminant categories in Table 5.1 provide some general treatment options, there will be differences in the specific removal of each contaminant by the different treatment processes. As well, the treatment alternative's efficiency for contaminants may vary depending on the type of source water, influent contaminant concentration, and operating conditions. Therefore, a literature survey was conducted to comprehensively assess the removal efficiency of each critical contaminant by the various treatment options. Table 5.2 provides a detailed summary of the treatment alternatives for each critical contaminant, together with information available in published studies on removal under specific conditions.

5.3.1 Technologies for E.coli Removal/Inactivation

Chemical disinfection with chlorine, chlorine dioxide, and ozone are effective in disinfecting or inactivating *E. coli* in wastewater, with more than 4 log reduction shown in several studies (Mezzanotte *et al.*, 2007; Montemayor *et al.*, 2008; Bischoff *et al.*, 2013; Miranda *et al.*, 2014). Chlorine is the most widely used disinfectant, which can oxidize bacteria and viruses. However, chlorine can react with organic matter in wastewater effluents to form harmful

chlorinated compounds, which can cause risk to the safety of groundwater. Also, there is a discharge limit (0.02 mg/L) for chlorine in the Canadian wastewater systems regulation (Government of Canada, 2014), due to its potential ecological effects. Therefore, dechlorination should be also applied in the wastewater treatment to remove residual chlorine (U.S.EPA, 2000). Chlorine dioxide is sometimes as effective as chlorine. However, it is difficult to work with this compound and therefore it's not widely used (Health Canada, 2012b). As a strong oxidant, ozone is also efficient for the inactivation of *E.coli*. However, the level of biodegradable organics may increase after ozone treatment and promote bacterial regrowth in the groundwater. The performance of chemical disinfection is often related to CT values where CT is the product of "C" (the residual concentration of disinfectant, measured in mg/L) and "T" (the disinfectant contact time, measured in minutes). Normally, a higher CT value can achieve a greater inactivation.

More recently, UV disinfection has also been used to inactivate microorganisms. Similar to chemical disinfection, UV disinfection performance is influenced by the irradiation dose. For example, a 4.3 log reduction of *E.coli* was found by Bischoff *et al.* (2013) using 15 mJ/cm² UV. A different study using 20 mJ/cm² UV found that *E.coli* was reduced by 5 log (Nasser *et al.*, 2006). Membrane filtration is another effective technology for the removal of *E.coli*. Li *et al.* (2008) used an ultrafiltration membrane to achieve 4 log *E.coli* removal. In addition, during the MAR process, soil aquifer treatment often plays an important role for the treatment of *E.coli*. Greater than 4 log reduction of *E.coli* was reported in the studies made by Levantesi *et al.* (2010) and Abel *et al.* (2014). However, this natural treatment is often influenced by the subsurface characteristics, and is difficult to control. Therefore, soil aquifer treatment will not be included in the discussion of treatment options for MAR.

5.3.2 Technologies for Giardia Removal/Inactivation

In comparison to bacteria and viruses, *Giardia* cysts are relatively resistant to the common chemical disinfectant chlorine. High chlorine concentrations and long contact times are often

required to inactivate *Giardia* to a satisfactory level (Health Canada, 2012a). As a strong oxidant, ozone can effectively inactivate *Giardia* in wastewater, and studies have shown a reduction of up to 3 log (Passos *et al.*, 2014). The CT values for ozone disinfection are impacted by water temperature. In general, at lower water temperatures, ozone is less effective and therefore a higher ozone dosage and longer contact time are needed compared with higher water temperatures (Health Canada, 2012a). UV disinfection is also quite effective for *Giardia* inactivation. At a UV dosage of 10 mJ/cm², 4 log reduction was reported by both Shin *et al.* (2009) and Linden *et al.* (2002). To reduce shielding caused by suspended particles and allow better light penetration, UV disinfection is often applied after particle removal steps such as filtration. Granular filtration is another practical method to achieve a high removal of *Giardia*. A study conducted by Nieminski and Ongerth (1995) found that granular dual-media (sand and anthracite) filtration can achieve a 3 log reduction of *Giardia*. However, other studies using GAC media reported a lower removal efficiency (2 log reduction) for *Giardia* (Hijnen *et al.*, 2010; Bichai *et al.*, 2014). Membrane filters can also effectively remove protozoan cysts, and microfiltration and ultrafiltration membranes showed greater than 5.2 log reductions for *Giardia* in a study conducted by Jacangelo *et al.* (1995).

5.3.3 Technologies for Cryptosporidium Removal/Inactivation

Cryptosporidium oocysts are much more resistant to chlorine-based disinfection than *Giardia* since chlorine cannot penetrate the thick protective oocyst wall (Health Canada, 2012a). However, ozone is an effective inactivating agent against *Cryptosporidium*, and 3.5 log and 3 log oocyst reduction were respectively reported in studies conducted by Rennecker *et al.* (1999) and Craik *et al.* (2003). UV disinfection can significantly reduce the concentrations of *Cryptosporidium* by around 4 log (Clancy *et al.*, 1998; Craik *et al.*, 2001). Larger than 3 log reduction of *Cryptosporidium* oocysts were achieved by granular media filtration under optimized filter conditions (Swertfeger *et al.*, 1997; Emelko, 2003). However, the decline in oocyst removal by several log units has been observed under some conditions, such as filter breakthrough at the end of a filtration cycle (Huck *et al.*, 2002). Similar to *Giardia*,

membrane filtration is able to achieve an absolute removal of *Cryptosporidium*, and microfiltration has been shown to result in 6 log reduction (States *et al.*, 2000; Lovins III *et al.*, 2002).

5.3.4 Technologies for Nitrate and Nitrite Removal

Nitrite is not stable and can react with oxygen in water to form nitrate. Therefore, the nitrite concentration in wastewater effluent is not very high and treatment methods are rarely reported (Department of National Health and Welfare, 1993). In addition, many treatment technologies can effectively remove both nitrite and nitrate (Health Canada, 2013). Therefore, treatments discussed below will be based on nitrate removal. In wastewater treatment plants, denitrification processes can biologically reduce nitrate to nitrogen. However, this process requires the addition of an electron donor such as organic compounds (e.g. ethanol, acetic acid) and inorganic compounds (e.g. hydrogen, sulphur), which need to be post-treated. Therefore, this process is not recommended for potable reuse. Therefore, physical-chemical processes are more favored and will be discussed.

As the most common nitrate removal process for drinking water, ion exchange can reduce the concentrations of nitrate by up to 69% (Richard, 1989). During the ion exchange process, nitrate ions in the water are exchanged with chloride ions, and the capacity of the resin is gradually exhausted. The regeneration of the resin must be conducted when it reaches capacity. RO is also an effective technology to lower high concentrations of nitrate in water. Nitrate removal efficiencies of 95.7% and 98% were respectively reported in Cevaal *et al.* (1995) and Goncharuk *et al.* (2013). All membranes are susceptible to fouling, and since RO membranes have a small pore size, they are also susceptible to scaling. Therefore, pretreatments including softening, filtration, coagulation, and the addition of anti-scaling agents are often required. Nanofiltration membranes can also remove nitrate, and it was found that NF 90 and ESNA1-LF membranes can remove 90% of nitrate (Santafé-Moros *et al.*, 2005), while NF 70 membrane can only reject 76% of nitrate (Van der Bruggen *et al.*, 2001).

The difference between these two NF membrane efficiencies may be because adsorption can play an important role in the nanofiltration process, and some types of NF membrane have suitable surface characteristics more inclined to remove nitrate ions from water. Electrodialysis is a less commonly used technology but can achieve nitrate rejection of around 80% (Chebi and Hamano, 1995; Hell *et al.*, 1998). The process uses electric potential to remove nitrate by ion exchange membranes. To reduce membrane scaling, the polarity of electrodes is reversed several times every hour in the operation to change the ion movement direction. In addition, chemical reduction of nitrate by the use of metals also shows effectiveness. Different types of metals can remove nitrate from water. For example, a nitrate removal of 80% can be achieved in a chemical reduction process using metallic iron (Huang *et al.*, 1998). Luk and Au-Yeung (2002) demonstrated a 62% reduction in nitrate from an initial concentration of 20 mg/L by adding 300 mg/L of aluminum powder into groundwater at a pH of 10.7.

5.3.5 Technologies for Ammonia Removal

Ammonia has two forms in water: the non-ionized form (NH₃) and the ammonium cation (NH₄⁺). The sum of these two forms is called total ammonia. The percentage of these two species is mainly influenced by pH and temperature, which influence the dissociation constant (pK_a) of ammonia. At 25 °C, the pK_a value for ammonia dissociation is 9.56. In practical terms, the amount of non-ionized ammonia present can be determined by the following equation (Government of Canada, 2014):

$$\text{NH}_3 = \text{total ammonia} \times \frac{1}{1 + 10^{5.5 - \text{pH}}}$$

Since the pH of municipal wastewater effluent is usually around 7, NH₃ does not account for a large percentage of total ammonia (0.27%). Therefore, the technologies mainly used to remove NH₄⁺ will be discussed. In addition, since nitrification processes are already implemented in WWTPs to oxidize ammonia, the following discussion will focus on the physical-chemical processes for the removal of ammonia.

As the most commonly used technology to remove ions, ion exchange shows good performance for the removal of NH_4^+ . Vassileva and Voikova (2009) and Šiljeg *et al.* (2010) used clinoptilolite zeolite as the resin to reach up to 100% of ammonia reduction. RO is also quite effective to reduce the concentration of NH_4^+ . Compared with an NF membrane that could only achieve up to 27% of nitrate removal (Kurama *et al.*, 2002), an RO membrane was found capable of rejecting 97% of 5 mg/L NH_4^+ (Kurama *et al.*, 2002) and 95% of 6.6 mg/L NH_4^+ (Koyuncu *et al.*, 2001).

5.3.6 Technologies for Phosphorus Removal

Treatment technologies available for the removal of phosphorus include biological and physical-chemical processes. Since biological processes are mainly used in wastewater treatment plants to treat raw wastewater and physical-chemical processes are more applied for the reclamation of wastewater effluent, only physical-chemical technologies will be discussed.

The addition of chemicals to precipitate phosphorus has long been used for phosphorus removal. This treatment alternative can remove greater than 90% of phosphorus from water by adding alum (Lin and Carlson, 1975; Shannon and Verghese, 1976). Membrane technologies have been of greater interest for phosphorus reduction. High phosphorus removals of around 95% were reported in studies using ultrafiltration and nanofiltration (Dietze *et al.*, 2003; Acero *et al.*, 2010; Justyna and Katarzyna, 2013; dos Santos *et al.*, 2014).

5.3.7 Technologies for Aluminum Removal

Aluminum is often added as coagulant in water treatment processes. The residual concentration of soluble aluminum is determined by pH. Particulate aluminum can be removed by sedimentation and filtration. Thus, to achieve a low concentration of aluminum following filtration, the pH prior to filtration must be such that the proportion of total aluminum that is in the particulate form is maximized. For this reason, conventional drinking

water treatment processes (coagulation, sedimentation and filtration) would not typically be considered for removal of elevated concentrations of aluminum that might be present in a wastewater effluent. According to studies conducted by Petrie *et al.* (1984) and Venkataramani *et al.* (1988), ion exchange can achieve over 90% removal for aluminum. Membrane processes including reverse osmosis and electrodialysis also show excellent performance for the removal of aluminum with reductions from 90% to 100% (Srinivasan *et al.*, 1999). As a cost effective method, chemical reduction can effectively reduce 0.15 mg/L aluminum concentration by 96.7% by using apatite (calcium phosphate minerals) (Nilson *et al.*, 1992).

5.3.8 Technologies for Manganese Removal

Manganese exists in both dissolved and undissolved forms in water. Since the undissolved forms are precipitates, which can be easily removed by the filtration process that could be present in advanced wastewater treatment plants, the dissolved forms of manganese will be the focus of treatment.

A common way to remove dissolved manganese is oxidation, which uses strong oxidizing agents such as ozone or potassium permanganate to oxidize Mn (II) to Mn (IV), a form that can readily precipitate and later be filtered. El Araby *et al.* (2009) achieved 83% removal of manganese by using ozone as the oxidant, and Zhu *et al.* (2009) oxidized 71% of manganese by using potassium permanganate. The differences of manganese removal efficiency by these two oxidants may be because ozone has the stronger oxidation ability than potassium permanganate. A combination of oxidation and membrane filtration also demonstrates effectiveness for manganese reduction, with over 90% removal efficiency (Jimbo and Goto, 2001; Teng *et al.*, 2001). As treatments to directly remove dissolved manganese, ion exchange and adsorption also show good performance, and 85% to 100% manganese reduction were found in previous studies (White and Asfar-Siddique, 1997; Fune *et al.*, 2014; Qomi *et al.*, 2014).

5.3.9 Technologies for Chloride Removal

Chloride is costly to remove from water. Only advanced water treatments, including adsorption and reverse osmosis, are effective for the treatment of chloride. Over 80% of chloride removal from wastewater were achieved by both Abu-Arabi *et al.* (2013) using a new type of adsorbent (IRA-402) and Iakovleva *et al.* (2015) using solid wastes (RH and DI-60) as the adsorbent. In another study, Jevtitich *et al.* (1986) used an aromatic polymeric reverse osmosis membrane to reduce the chloride concentration in wastewater by 91%.

5.3.10 Technologies for Atrazine Removal

Conventional water treatments such as coagulation, filtration, sedimentation, clarification, softening, and chlorination are not effective for the removal of atrazine (Lazorko-Connon and Achari, 2009). AOPs can produce hydroxyl radicals to oxidize and mineralize atrazine. With the addition of H₂O₂ and ultraviolet light, over 90% removal of atrazine were achieved in studies conducted by Antoniou and Andersen (2014) and James *et al.* (2014). GAC and PAC are normally used in water treatment plants for the removal of pesticide including atrazine. The treatment efficiencies of adsorption vary among different conditions such as raw water quality, adsorbent dosage and contact time variations. Under optimum conditions, up to 99% and 98% treatment efficiency for atrazine was achieved by GAC and PAC, respectively (Selm and Wang, 1994; Snyder *et al.*, 2007; Zou *et al.*, 2014). However, since natural organic matter in the source water may compete with atrazine adsorption, performance is often influenced by the source water characteristics. Membrane filtration is another available technology to remove atrazine. Treatment performance mainly depends on the pore size of membrane. High pressure membranes, including RO and NF, can remove from around 80% to 98% of atrazine from water (Chian *et al.*, 1975; Devitt *et al.*, 1998; Heo *et al.*, 2013; Shen *et al.*, 2014). However, a low pressure ultrafiltration membrane was reported to remove less than 40% of atrazine from water (Yoon *et al.*, 2006).

5.3.11 Technologies for Diuron Removal

Similar to atrazine, only a small amount of diuron can be removed by conventional drinking water treatment. El-Dib and Aly (1977) used 100 mg/L ferric sulfate as the coagulant to remove only 20% of diuron from water. UV-based AOPs were found to be a powerful tool to reduce diuron concentrations. With the addition of Fe^{3+} , 82% of diuron was degraded during UV radiation, with its concentration decreasing from 11.7 mg/L to 2.1 mg/L (Djebbar *et al.*, 2008). When Fe^{3+} and H_2O_2 were both used as chemical reagents to react with diuron under UV light, 95% and 100% of diuron removals were respectively reported by Djebbar *et al.* (2008) and Pérez *et al.* (2006). Even though ozone is a strong oxidant to mineralize trace organics, it cannot effectively degrade diuron. Ormad *et al.* (2010) only achieved 23% of diuron removal by using 3 mg/L O_3 . In terms of adsorption, GAC and PAC were found to be able to remove 90% and 95%, respectively, of diuron from water (Baup *et al.*, 2002). NF is also an efficient means to remove diuron, and resulted in 90% and 85% of diuron retention reported by Hofman *et al.* (1993) and Benitec *et al.* (2009), respectively.

5.3.12 Technologies for Di(2-ethylhexyl)phthalate (DEHP) Removal

DEHP can be effectively treated by various types of treatment technologies. Conventional drinking water treatment can achieve from moderate to excellent treatment performance for DEHP. One study by Theepharakaspan *et al.* (2011) used FeCl_3 as the coagulant to remove 56% of DEHP from wastewater. Filtration was also studied for the removal of DEHP from wastewater, and over 80% reduction was achieved since DEHP was potentially sorbed on suspended matter in wastewater (Meng *et al.*, 2013; Mailler *et al.*, 2014). AOPs are another effective technology to remove DEHP. Several types of AOPs ($\text{H}_2\text{O}_2+\text{Fe}^{2+}$, $\text{UV}+\text{H}_2\text{O}_2$, $\text{O}_3+\text{Catalysts}$) have been used to reduce the DEHP concentration by 70% - 85% (Hammad Khan and Jung, 2008; Esmaeli *et al.*, 2011; Park and Kim, 2012). In addition, nanofiltration is capable of removing around 90% of DEHP from water (Shen *et al.*, 2014).

5.3.13 Technologies for Nitrilotriacetic Acid (NTA) Removal

Based on the structure and chemical properties of NTA, oxidation is the most effective technology to remove NTA. As an effective oxidant, ozone was often studied to reduce the NTA concentration in water, and 75% to 90% reduction were achieved in experiments conducted by Games and Staubach (1980) and Hrubec *et al.* (1984).

5.3.14 Technologies for Perfluorooctane Sulfonate (PFOS) Removal

Due to the high hydrophilicity and low concentrations, PFOS is difficult to be removed by conventional coagulation processes (Rahman *et al.*, 2014). Only 6.6% of PFOS reduction was achieved in a study using alum as coagulant (Xiao *et al.*, 2013). Adsorption is a desirable treatment choice for the removal of PFOS. Around 66% removal was reported in several studies using GAC as the adsorbent to treat water containing PFOS (Eschauzier *et al.*, 2012; Flores *et al.*, 2013). Hansen *et al.* (2010) observed a maximum 97% of PFOS reduction by adding PAC into water. High pressure membranes, including NF and RO, can also effectively remove over 99% of PFOS (Tang *et al.*, 2006; Lipp *et al.*, 2010; Appleman *et al.*, 2013).

5.3.15 Technologies for Perfluorooctanoate (PFOA) Removal

Similar to PFOS, PFOA is also resistant to conventional drinking water treatment. Xiao *et al.* (2013) found that PFOA was not removed using 30 mg/L alum. PFOA can be removed by adsorption, and indications are that PAC is more effective to remove PFOA than GAC. Around 50% removals were achieved in the studies conducted by Eschauzier *et al.* (2012) and Flores *et al.* (2013) using GAC to adsorb PFOA. However, when around 30 mg/L PAC were added into water, 88% and 89% of PFOA removals were reported by Hansen *et al.* (2010) and Yu *et al.* (2014), respectively. However, the actual experimental conditions of the studies would need to be examined in more detail before a definitive statement could be made regarding the relative efficiency of GAC and PAC. Due to the small membrane pore size, NF and RO membranes were found to be quite effective to remove PFOA. Thompson *et al.*

(2011), Lipp *et al.* (2010), and Appleman *et al.* (2013) achieved greater than 97% of PFOA removals by using these two types of membranes.

5.3.16 Technologies for Ibuprofen Removal

As a conventional drinking water treatment process, coagulation is ineffective to remove ibuprofen from water. Kim *et al.* (2007) found that there is a 16% increase in ibuprofen concentration after coagulation in the drinking water treatment plant, likely due to experimental conditions such as analytical variability and plug-flow timing of sample collection. However, Hallé (2009) found good removal of ibuprofen by drinking water biofilters. Ibuprofen can also be degraded during oxidation processes. Based on the results of a study by Huber *et al.* (2003), 77% ibuprofen reduction was found when using ozone alone as the oxidant. With the combination of ozone and H₂O₂, greater ibuprofen removals (98%-100%) were achieved (Zwiener and Frimmel, 2000; Huber *et al.*, 2003). Under the optimum conditions, AOPs using UV and H₂O₂ can remove 90% of ibuprofen (Shu *et al.*, 2013). Adsorption is also considered as a promising technology to remove ibuprofen. Over 90% of ibuprofen was reported to be adsorbed on to GAC and PAC in studies by Mestre *et al.* (2011), Jung *et al.* (2013), and Noutsopoulos *et al.* (2014). High ibuprofen rejection (around 90%) by NF membranes demonstrates the effectiveness of high pressure membrane filtration to treat water with ibuprofen (Beier *et al.*, 2010; Botton *et al.*, 2012).

5.3.17 Technologies for Carbamazepine Removal

The elimination of carbamazepine by coagulation is not efficient. Based on the study conducted by Kim *et al.* (2007), carbamazepine concentration even increased by 9.4% after the coagulation process in the full-scale drinking water treatment plant. The increase was likely due to the effect of particle removal on the analytical method. However, AOPs have been shown to be effective in the removal of carbamazepine. The application of O₃ and UV were found to degrade 97.5% to 100% of carbamazepine in wastewater (Ternes *et al.*, 2003; Gebhardt and Schröder, 2007). When UV+H₂O₂ and UV+Catalysts were used in AOPS,

around 80% to 90% of carbamazepine was degraded (Rizzo *et al.*, 2009; Rosario-Ortiz *et al.*, 2010; Chong and Jin, 2012; Lester *et al.*, 2014). The performance of oxidation for the removal of carbamazepine mainly depends on the CT value (ozone dosage × contact time). When 8.7 mg/L of ozone was added into wastewater for 18 minutes (CT value of 157 mg-min/L), 98% of carbamazepine removal was achieved (Lei and Snyder, 2007), whereas Nakada *et al.* (2007) used 3 mg/L ozone for 27 minutes (CT value of 81 mg-min/L) and obtained 81% of carbamazepine removal. Adsorption is another efficient process to remove carbamazepine, and 80% to 90% reduction were achieved by Ternes *et al.* (2002), Yang *et al.* (2011), Altmann *et al.* (2014), and Ruhl *et al.* (2014) using GAC and PAC as the adsorbents. NF and RO membranes are also effective for carbamazepine rejection. Gur-Reznik *et al.* (2011) and Beier *et al.* (2010) found 92% and 88% of carbamazepine removal, respectively, from wastewater by using NF membranes, but RO membranes could remove 97.6% and 99.86%, respectively.

5.3.18 Technologies for Diclofenac Removal

Both coagulation and granular filtration were found to be ineffective for the removal of diclofenac. Only 3% of diclofenac was removed when 5 mg/L alum was added into surface water (Simazaki *et al.*, 2008). When a sand filter was used to treat surface water containing 1 mg/L diclofenac, 12% removal efficiency was achieved (Rigobello *et al.*, 2013). Oxidation processes are efficient for the removal of diclofenac. Kim *et al.* (2009 a,b) obtained 98% to 100% removal efficiency by using UV+H₂O₂, O₃+UV, or O₃ to degrade diclofenac. Similar with other pharmaceuticals, GAC and PAC were also effective for the removal of diclofenac. Around 90% diclofenac reductions were achieved in Ternes *et al.* (2002), Yang *et al.* (2011), Ruhl *et al.* (2014), and Altmann *et al.* (2014) studies which investigated the ability of GAC and PAC for diclofenac elimination. High pressure membrane filtration is also a suitable technology to deal with diclofenac removal. Beier *et al.* (2010), Sahar *et al.* (2011), and Maria *et al.* (2012) found that RO and NF membranes could remove over 95% of diclofenac from wastewater.

5.3.19 Technologies for Erythromycin Removal

One study conducted by Boleda *et al.* (2011) shows that conventional drinking water treatment processes including coagulation/sedimentation/filtration can remove 85.5% of erythromycin. Oxidation processes using ozone or ozone with catalysts also have good performance to degrade erythromycin and complete or almost complete removals (97% - 100%) were observed (Kim *et al.*, 2009a b; Derrouiche *et al.*, 2013). PAC was found to be more efficient for removing erythromycin from water than GAC. Greater than 90% removal was found with the addition of PAC to water (Serrano *et al.*, 2011; Liu *et al.*, 2013), while only 60% - 75% erythromycin reduction were achieved by using GAC (Boleda *et al.*, 2011; Yang *et al.*, 2011). However, the actual experimental conditions of the studies would need to be examined in more detail before a definitive statement could be made regarding the relative efficiency of GAC and PAC. Different from other emerging contaminants, which can be effectively removed by membrane filtration, erythromycin can only be partially rejected by reverse osmosis (75%) and ultrafiltration (35.4%) (Boleda *et al.*, 2011). This difference may be the low erythromycin influent concentration and experiment variability.

5.3.20 Technologies for Sulfamethoxazol Removal

Fewer studies have been conducted to evaluate the removal of sulfamethoxazol. Nakada *et al.* (2007) found that granular filtration can only remove 26.8% of sulfamethoxazol using sand filter media with a flow rate of 110 m/day, and retention time of 27 minutes. This may be because sulfamethoxazol is hydrophilic and not easily associated with particulates, which can be removed by filtration. However, when 3 mg/L ozone was added into wastewater for 27 minutes, 87.4% of sulfamethoxazol was removed (Nakada *et al.*, 2007).

5.3.21 Technologies for Nonylphenol Removal

Conventional drinking water treatment showed moderate performance for the removal of nonylphenol. Around 70% of nonylphenol reduction was reported in previous studies (Nam *et*

al., 2014; Padhye *et al.*, 2014). As a promising technology to degrade trace organics, oxidation processes achieved 87% nonylphenol reduction using ozone (Zhang *et al.*, 2008) and 100% with the combination of UV and H₂O₂ (Karci *et al.*, 2013a, 2013b). GAC adsorption had better removal of nonylphenol than PAC adsorption, and many studies (Choi *et al.*, 2005; Hernández-Leal *et al.*, 2011) showed over 90% of nonylphenol removals by GAC experiments, and Delgado *et al.* (2012) found only 52% nonylphenol removal by PAC. Reverse osmosis membranes also showed high rejection of nonylphenol in the experiments by Al-Rifai *et al.* (2011) and Garcia *et al.* (2013). Although nonylphenol was investigated by a lot of studies, this chemical is difficult to use in research because of the potential for appreciable system losses during experiments (Hallé, 2009). Therefore, great caution should be made when studying this chemical.

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
<i>E.coli</i>	UV disinfection	Wastewater	10 ⁴ -10 ⁵ MPN/100 mL	15 mJ/cm ² UV	4.3 log reduction	Bischoff <i>et al.</i> , 2013
		Wastewater	10 ⁵ -10 ⁶ CFU/100 mL	20 mJ/cm ² UV	5 log reduction	Nasser et al., 2006
	Chemical disinfection: Chlorine	Wastewater	10 ⁵ CFU/100 mL	5 mg/L Cl ₂ Contact time:20 min	4.5 log reduction	Montemayor <i>et al.</i> , 2008
		Wastewater	8×10 ³ -1.6×10 ⁴ CFU/100 mL	5 mg/L Cl ₂ Contact time: 7 min	4.2 log reduction	Mezzanotte <i>et al.</i> , 2007
	Chemical disinfection: Chlorine dioxide (ClO ₂)	Wastewater	10 ⁴ -10 ⁵ MPN/100 mL	2.4 mg/L ClO ₂ Contact time: 25 min	4.1 log reduction	Bischoff <i>et al.</i> , 2013
	Chemical disinfection: Ozone	Wastewater	8×10 ³ -1.6×10 ⁴ CFU/100 mL	5.3 mg/L O ₃ Contact time: 6.4 min	≥4 log reduction	Mezzanotte <i>et al.</i> , 2007
		Wastewater	3.4×10 ⁵ MPN/100 mL	5 mg/L O ₃ Contact time: 5 min	4.99 log reduction	Miranda <i>et al.</i> , 2014
	Membrane filtration: UF	Wastewater	10 ⁴ CFU/100 mL	Membrane type: Polyacrylonitrile membrane TMP: 0.12 bar	4 log reduction	Li <i>et al.</i> , 2008
	Soil aquifer treatment	Wastewater	2.2×10 ³ -8.4×10 ⁴ CFU/100 mL	Recharge rate: 6.9 Mm ³ year ⁻¹ Unconfined, alluvial aquifer	4.7 log reduction	Levantesi <i>et al.</i> , 2010
		Wastewater	6.2×10 ⁶ CFU/100 mL	Recharge rate: 1.2 m ³ year ⁻¹ Silica Sand Column	4.3 log reduction	Abel <i>et al.</i> , 2014

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
<i>Giardia</i>	UV disinfection	Wastewater	10 ⁵ cysts/L	10 mJ/cm ² UV	4 log reduction	Shin <i>et al.</i> , 2009
		Phosphate buffered saline	10 ⁴ cysts/L	10 mJ/cm ² UV	4 log reduction	Linden <i>et al.</i> , 2002
	Chemical disinfection: Ozone	Wastewater	10 ⁴ cysts/L	30 mg/L O ₃ Contact time: 5 min	3 log reduction	Passos <i>et al.</i> , 2014
	Granular media filtration	Surface water	5×10 ⁶ cysts/L	Media: sand (60.96 cm) & anthracite (50.8 cm) Loading rate: 14 m/h	3 log reduction	Nieminski and Ongerth, 1995
		Wastewater	4.8×10 ⁴ cysts/L	Media: GAC (1m) U _c =d ₆₀ /d ₁₀ =1.7 ES: d ₁₀ =0.65 mm Filtration rate: 5m/h	2 log reduction	Bichai <i>et al.</i> , 2014
		Surface water	10 ⁵ cysts/L	Media: GAC (1.35 m) U _c =d ₆₀ /d ₁₀ =1.7 ES: d ₁₀ =0.55 mm Filtration rate: 5m/h	2.1 log reduction	Hijnen <i>et al.</i> , 2010
	Membrane filtration: UF	Surface water	1.5×10 ⁵ cysts/L	Membrane type: Hollow fiber 100,000 Da membrane Feed pressure: 0.3-2 bar	≥5.2 log reduction	Jacangelo <i>et al.</i> , 1995

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
<i>Giardia</i>	Membrane filtration: UF	Wastewater	1.83×10^3 cysts/L	Membrane type: Submerged hollow fiber TMP: 0.4-0.7 bar	≥ 3.6 log reduction	Lonigro <i>et al.</i> , 2006
	Membrane filtration: MF	Surface water	1.5×10^5 cysts/L	Membrane type: Hollow fiber 0.2 μm membrane Feed pressure: 0.6-2 bar	≥ 5.2 log reduction	Jacangelo <i>et al.</i> , 1995
	SAT	Wastewater	0.24-6.2 cysts/L	Recharge rate: $6.9 \text{ Mm}^3 \text{ year}^{-1}$ Unconfined, alluvial (mainly sand and gravel) aquifer	≥ 2.8 log reduction	Levantesi <i>et al.</i> , 2010
		Wastewater	Around 3×10^3 cysts/L	Retention time: 48 h	2.7 log reduction	Chávez <i>et al.</i> , 2011
<i>Cryptosporidium</i>	UV disinfection	Surface water	3.8×10^6 oocysts/L	18 mJ/cm^2 UV	4 log reduction	Clancy <i>et al.</i> , 1998
		Surface water	1.5×10^6 oocysts/L	22 mJ/cm^2 UV	3.7 log reduction	Craik <i>et al.</i> , 2001
	Chemical disinfection: ozone	Surface water	1.25×10^6 oocysts/L	2 mg/L Ozone Contact time: 7.5 min	3.5 log reduction	Rennecker <i>et al.</i> , 1999
		Tap water	10^5 oocysts/L	0.62 mg/L Ozone Contact time: 15 min	3 log reduction	Craik <i>et al.</i> , 2003

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
<i>Cryptosporidium</i>	Granular media filtration	Surface water	10 ⁵ oocysts/L	Loading rate: 7.5 m/h Media: anthracite (ES: 0.98 mm, UC=1.5) 700 mm; sand (ES: 0.5 mm, UC=1.5) 300 mm	4 log reduction	Emelko, 2003
		Surface water	2.5×10 ⁵ -1.1×10 ⁶ oocysts/L	Loading rate: 12.6 m/h Media: anthracite (ES: 0.8 mm) 900 mm Sand (ES: 0.4) 300 mm	3.2 log reduction	Swertfeger <i>et al.</i> , 1999
		Surface water	1.6×10 ⁵ oocysts/L	Media: GAC (1m), UC: U _c =1.7 ES: d ₁₀ =0.65 mm Filtration rate: 5m/h	1.2 log reduction	Bichai <i>et al.</i> , 2014
		Surface water	1.6×10 ⁵ oocysts/L	Media: GAC (1.35 m) UC: U _c =d ₆₀ /d ₁₀ =1.7 ES: d ₁₀ =0.55 mm Filtration rate: 5m/h	1.2 log reduction	Hijnen <i>et al.</i> , 2010
	Membrane filtration: MF	Surface water	10 ⁷ oocysts/L	Membrane type: Hollow fiber CA derivative Feed pressure: 2 bar	6 log reduction	Lovins III <i>et al.</i> , 2002

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
<i>Cryptosporidium</i>	Membrane filtration: MF	Drinking water	10 ⁸ oocysts/L	Membrane type: Polypropylen microfiltration Filtration rate: 20,833 L/h	6 log reduction	States <i>et al.</i> , 2000
	SAT	Wastewater	0.075-0.4 oocysts/L	Recharge rate: 6.9 Mm ³ year ⁻¹ Unconfined, alluvial (mainly sand and gravel) aquifer	≥1.6 log reduction	Levantesi <i>et al.</i> , 2010
		Storm water	1.2 oocysts/L	Retention time: 223 days	Most likely 2.8 log reduction	Page <i>et al.</i> , 2010
Nitrate (as nitrogen)	Ion exchange	Tap water	20 mg/L	Nitrate-selective resin Flow rate: 20 BV/h	65%	Clifford and Liu, 1993
		Groundwater	18 mg/L	Dowex SBRP resin Flow rate: 420,000 L/h	69%	Richard, 1989
	Membrane filtration: NF	Groundwater	62 mg/L	Membrane types: NF90 & ESNA1-LF Feed pressure: 4-16 bar	90%	Santafé-Moros <i>et al.</i> , 2005
		Groundwater	10 mg/L	Membrane types: NF70 Feed pressure: 10 bar	76%	Van der Bruggen <i>et al.</i> , 2001

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Nitrate (as nitrogen)	Membrane filtration: RO	Groundwater	13.7 mg/L	Membrane types: Spiral-wound polyamide thin-film composite membrane Feed pressure: 11.7 bar	95.7%	Cevaal <i>et al.</i> , 1995
		Groundwater	11.3 mg/L	Membrane types: “Dead- end” cylindrical cell membrane Feed pressure: 20 bar	98%	Goncharuk <i>et al.</i> , 2013
	Electrodialysis	Groundwater	27 mg/L	Hydraulic capacity: 1m ³ /h Membrane type: monovalent anion exchange membrane	83%	Hell <i>et al.</i> , 1998
		Surface water	18 mg/L	Membrane type: monovalent membrane	80%	Chebi and Hamano, 1995
	Chemical reduction	Deionized water	22.58 mg/L	pH<4, Fe ⁰ /NO ₃ >120 (g/g)	80%	Huang <i>et al.</i> , 1998
		Groundwater	20 mg/L	pH: 10.7, Temperature: 25°C, aluminum dosage: 300 mg/L	62%	Luk and Au-Yeung, 2002

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Ammonia (as nitrogen)	Ion exchange	Groundwater	1.15 mg/L	Resin: Clinoptilolite Zeolite Flow rate: 420 L/h	100%	Šiljeg <i>et al.</i> , 2010
		Deionized water	136 mg/L	Resin: Clinoptilolite Zeolite Capacity: 18.40 mg/g ClNa	100%	Vassileva and Voikova, 2009
	Membrane filtration: NF	Surface water	5 mg/L	Membrane type: N30F Feed pressure: 6 bar pH:7.6 Flow rate: 0.078 L/h	27%	Kurama <i>et al.</i> , 2002
	Membrane filtration: RO	Surface water	5 mg/L	Membrane type: Desal-3BSE Membrane Feed pressure: 11 bar	97%	Kurama <i>et al.</i> , 2002
		Drinking water	6.6 mg/L	Membrane type: Thin film composite membrane Feed pressure: 40 bar	95%	Koyuncu <i>et al.</i> , 2001

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Total Phosphorus	Chemical reduction	Wastewater	10 mg/L	Chemical: Alum Dosage: 10 mg/L	94%	Lin and Carlson, 1975
		Wastewater	6 mg/L	Chemical: Alum Dosage: 200 mg/L	99%	Shannon and Verghese, 1976
	Membrane filtration: NF	Wastewater	0.4 mg/L	Membrane type: Thin film membrane Trans-membrane pressure (TMP): 30 bar	98.3%	Acerro <i>et al.</i> , 2010
		Surface water	2.2 mg/L	Membrane type: NF 90 Feed pressure: 10 bar	96.7%	dos Santos <i>et al.</i> , 2014
	Membrane filtration: UF	Surface water	0.336 mg/L	Membrane type: Polyacrylonitrile membrane Trans-membrane pressure (TMP): 2 bar	92%	Dietze <i>et al.</i> , 2003
		Deionized water	15 mg/L	Membrane type: Miceller enhanced membrane Trans-membrane pressure (TMP): 2 bar	95%	Justyna and Katarzyna, 2013

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Aluminum	Ion exchange	Tap water	0.27 mg/L	Resin type: IRA 400	90%	Petrie <i>et al.</i> , 1984
		Deionized water	N/A	Resin type: HTiO Loaded Resin Contact time: 2h	96%	Venkataramani <i>et al.</i> , 1988
	Membrane filtration: RO	Surface water	N/A	N/A	≥90%	Srinivasan <i>et al.</i> , 1999
	Electrodialysis	Surface water	N/A	N/A	≥90%	Srinivasan <i>et al.</i> , 1999
	Chemical reduction	Surface water	0.15 mg/L	Chemical: apatite (calcium phosphate minerals)	96.7%	Nilson <i>et al.</i> , 1992
Manganese	Oxidation	Groundwater	1 mg/L	3 mg/L Ozone pH=12	83%	El Araby <i>et al.</i> , 2009
		Surface water	0.14 mg/L	0.47 mg/L KMnO ₄	71%	Zhu <i>et al.</i> , 2009
	Ion exchange	Deionized water	5 mg/L	Resin type: Hydrous Manganese Dioxide	99%	White and Asfar-Siddique, 1997
	Adsorption	Deionized water	100 mg/L	Adsorbent: Carbonyl iron	95%	Funes <i>et al.</i> , 2014
		Distilled water	100 mg/L	Adsorbent: GAC	86.39%	Qomi <i>et al.</i> , 2014

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Manganese	Membrane filtration (with oxidation)	Groundwater	0.49 mg/L	Membrane types: UF & MF	92%	Jimbo and Goto, 2001
		Tap water	0.5 mg/L	Membrane types: MF	95%	Teng <i>et al.</i> , 2001
Chloride	Adsorption	Wastewater	20 mg/L	Adsorbent: DI-60 & RH	96%	Iakovleva <i>et al.</i> , 2015
		Wastewater	886 mg/L	Adsorbent: IRA-402	82.5%	Abu-Arabi <i>et al.</i> , 2013
	Membrane filtration: RO	Wastewater	N/A	Membrane types: Aromatic polyamide membrane	91%	Jevtitch <i>et al.</i> , 1986
Atrazine	AOPs: UV+H ₂ O ₂	Wastewater	0.002 mg/L	2000 mJ/cm ² UV 1-16 mg/L H ₂ O ₂	98%	James <i>et al.</i> , 2014
		Groundwater	1 mg/L	700 mJ/cm ² UV 5-6 mg/L H ₂ O ₂	90%	Antoniou and Andersen, 2014
	Adsorption: GAC	Groundwater	0.2 mg/L	GAC type: Calgon-Filtersorb 400 EBCT: 18 min	99%	Selm and Wang, 1994
		Wastewater	0.00065 mg/L	GAC type: Calgon- Filtrisorb 400 EBCT: 7.6 min	99%	Snyder <i>et al.</i> , 2007

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Atrazine	Adsorption: PAC	Surface water	0.1 mg/L	PAC dosage: 60 mg/L	98%	Zou <i>et al.</i> , 2014
		Wastewater	0.000227 mg/L	PAC dosage: 35 mg/L	93%	Snyder <i>et al.</i> , 2007
	Membrane filtration: RO	Surface water	7.34 mg/L	Membrane type: NS-100 Pressure: 13.8 bar	97.82%	Chian <i>et al.</i> , 1975
		Stock solution (Pure methanol)	4.31 mg/L	Membrane type: BW 30	93.7%	Heo <i>et al.</i> , 2013
	Membrane filtration: NF	Surface water	0.005 mg/L	Membrane type: NF 45	80%	Devitt <i>et al.</i> , 1998
		Surface water	0.005 mg/L	Membrane type: DL 1210	77.6%	Shen <i>et al.</i> , 2014
	Membrane filtration: UF	Surface water	0.00005 mg/L	Membrane type: SEPA Pressure: 4.45-5.04 bar	≤40%	Yoon <i>et al.</i> , 2006
Diuron	Conventional drinking water treatment: Coagulation	Surface water	8-10 mg/L	Coagulation type: ferric sulfate Dosage: 100 mg/L	20%	El-Dib and Aly, 1977
	AOPs: UV+Fe ³⁺	High-purity water	11.7 mg/L	4.83×10 ⁻⁶ E/S UV 56 mg/L Fe ³⁺ Contact time: 20 min	82%	Djebbar <i>et al.</i> , 2008

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Diuron	AOPs: UV+Fe ³⁺ +H ₂ O ₂	High-purity water	11.7 mg/L	4.83×10 ⁻⁶ E/S UV 56 mg/L Fe ³⁺ , 34 mg/L H ₂ O ₂ Contact time: 20 min	95%	Djebbar <i>et al.</i> , 2008
		Wastewater	30 mg/L	60 mJ/cm ² UV 10 mg/L Fe ³⁺	100%	Pérez <i>et al.</i> , 2006
	Ozonation	Surface water	0.0005 mg/L	3 mg/L O ₃	23%	Ormad <i>et al.</i> , 2010
	Adsorption: GAC	Ultrapure water	10 mg/L	GAC amount: 100 mg Diameter: 8 mm Flow rate: 180 L/h	90%	Baup <i>et al.</i> , 2002
	Adsorption: PAC	Ultrapure water	10 mg/L	PAC dosage: 10 mg/L Contact time: 10 days	95%	Baup <i>et al.</i> , 2002
	Membrane filtration: NF	Surface water	N/A	Membrane type: PVD1	90%	Hofman <i>et al.</i> , 1993
		Ultrapure water	N/A	Membrane type: cellulose acetate Transmembrane pressure: 35 bar	85%	Benitez <i>et al.</i> , 2009
Di(2-ethylhexyl)phthalate (DEHP)	Conventional drinking water treatment: Granular media filtration	Wastewater	0.2828 mg/L	Media: 0.4-0.6 mm diameter quartz sands Filter depth: 800 mm	96.5%	Meng <i>et al.</i> , 2013
		Wastewater	0.013-0.066 mg/L	N/A	80%	Mailler <i>et al.</i> , 2014

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Di(2-ethylhexyl)phthalate (DEHP)	Conventional drinking water treatment: Coagulation	Wastewater	N/A	Coagulant: FeCl ₃	56%	Theeparaksapan <i>et al.</i> , 2011
	AOPs: H ₂ O ₂ +Fe ²⁺	Wastewater	20 mg/L	pH=3, 90 mg/L H ₂ O ₂ , 5 mg/L Fe ²⁺	85.6%	Esmaeli <i>et al.</i> , 2011
	AOPs: UV+H ₂ O ₂	Stock solution (methanol)	1 mg/L	600 mJ/cm ² UV 50 mg/L H ₂ O ₂	70%	Park and Kim, 2012
	AOPs: O ₃ +Catalyst	Deionized water	0.3 mg/L	Catalyst: Cr (III) Ozone: 96 mg/min, Contact time: 120min	75%	Hammad Khan and Jung, 2008
	Ozonation	Wastewater	0.007 mg/L	6 mg/L Ozone	80%	Zheng <i>et al.</i> , 2014
	Membrane filtration: NF	Surface water	0.005 mg/L	pH:5, Temperature: 5 °C, Transmembrane pressure (TMP): 0.4 MPa	89.8%	Shen <i>et al.</i> , 2014
Nitrilotriacetic Acid (NTA)	Ozonation	Surface water	0.35 mg/L	2 mg/L Ozone Contact time: 15 min	75%	Games and Staubach, 1980
		Tap water	0.5 mg/L	4 mg/L Ozone Contact time: 30 min	90%	Hrubec <i>et al.</i> , 1984

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Perfluorooctane Sulfonate (PFOS)	Conventional drinking water treatment: Coagulation	Surface water	0.00001 mg/L	Alum dosage: 110 mg/L	6.6%	Xiao <i>et al.</i> , 2013
	Adsorption: GAC	Surface water	0.000018 mg/L	EBCT=20 min Full-scale GAC filters	65.5%	Eschauzier <i>et al.</i> , 2012
		Surface water	0.000027 mg/L	GAC type: Chemviron F-400/ Norit ROW 0.8	66%	Flores <i>et al.</i> , 2013
	Adsorption: PAC	Groundwater	0.0014 mg/L	PAC dosage: 25 mg/L	97%	Hansen <i>et al.</i> , 2010
		Wastewater	0.2 mg/L	PAC dosage: 30 mg/L	90%	Yu <i>et al.</i> , 2014
	Membrane filtration: RO	Wastewater	0.5-1500 mg/L	Membrane type: Thin-film composite polyamide membrane Feed pressure: 13.8 bar	99%	Tang <i>et al.</i> , 2006
		Tap water+ demineralized water	0.0021 mg/L	Membrane type: XLE Feed pressure: 8 bar	99.9%	Lipp <i>et al.</i> , 2010
	Membrane filtration: NF	Tap water+ demineralized water	0.003 mg/L	Membrane type: NF90 Feed pressure: 6-7 bar	100%	Lipp <i>et al.</i> , 2010
		Deionized water	0.000866 mg/L	Membrane type: NF 270 Feed pressure: 9.7 bar	99%	Appleman <i>et al.</i> , 2013

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Perfluorooctanoate (PFOA)	Conventional drinking water treatment: Coagulation	Surface water	0.000083 mg/L	Alum dosage: 30 mg/L	-0.6% (0%)	Xiao <i>et al.</i> , 2013
	Adsorption: GAC	Surface water	0.000011 mg/L	GAC type: Chemviron F-400/ Norit ROW 0.8	45%	Flores <i>et al.</i> , 2013
		Surface water	0.0000088 mg/L	EBCT=20 min Full-scale GAC filters	50%	Eschauzier <i>et al.</i> , 2012
	Adsorption: PAC	Groundwater	0.0014 mg/L	PAC dosage: 25 mg/L	88%	Hansen <i>et al.</i> , 2010
		Wastewater	0.2 mg/L	PAC dosage: 30 mg/L	89%	Yu <i>et al.</i> , 2014
	Membrane filtration: RO	Wastewater	0.000052 mg/L	Rejection of substances >300 MW	97.3%	Thompson <i>et al.</i> , 2011
	Membrane filtration: NF	Tap water+ demineralized water	0.0029 mg/L	Membrane type: NF 90 Feed pressure: 8 bar	99.8%	Lipp <i>et al.</i> , 2010
		Deionized water	0.000664 mg/L	Membrane type: NF 270 Feed pressure: 9.7 bar	97%	Appleman <i>et al.</i> , 2013
Ibuprofen	Conventional drinking water treatments: Coagulation	Surface water	0.000015 mg/L	N/A	-16% (0%)	Kim <i>et al.</i> , 2007

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Ibuprofen	Ozonation	Surface water	N/A	2 mg/L O ₃ Contact time: 10 min	77%	Huber <i>et al.</i> , 2003
	AOPs: O ₃ +H ₂ O ₂	Surface water	N/A	2 mg/L O ₃ 0.7 mg/L H ₂ O ₂	100%	Huber <i>et al.</i> , 2003
		Wastewater	N/A	5 mg/L O ₃ 1.8 mg/L H ₂ O ₂	98%	Zwiener and Frimmel, 2000
	AOPs: UV+H ₂ O ₂	Milli-Q water	40 mg/L	2,470 mJ/cm ² UV 25 mg/L H ₂ O ₂	90%	Shu <i>et al.</i> , 2013
		Surface water	N/A	540 mJ/cm ² UV 6 mg/L H ₂ O ₂	68%	Kruihof and Martijn, 2013
	Adsorption: GAC	Deionized water	10.04 mg/L	GAC dosage: 20-450 mg/L Contact time: 26h	70.07%	Baccar <i>et al.</i> , 2012
		Ultrapure water	120 mg/L	GAC type: NSAES GAC dosage: 667 mg/L Contact time: 360 min	92%	Mestre <i>et al.</i> , 2011
	Adsorption: PAC	Stock solution (methanol)	0.001 mg/L	PAC dosage: 100 mg/L	92%	Noutsopoulos <i>et al.</i> , 2014
		Deionized water	N/A	PAC dosage: 50 mg/L	90%	Jung <i>et al.</i> , 2013

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Ibuprofen	Membrane filtration: NF	Tap water	N/A	Membrane type: 2521 spiral wound Flow rate: 350L/h	97%	Botton <i>et al.</i> , 2012
		Wastewater	0.0008 mg/L	Feed pressure: 7 bar	85.71%	Beier <i>et al.</i> , 2010
Carbamazepine	Conventional drinking water treatments: Coagulation	Surface water	0.0000048 mg/L	N/A	-9.4% (0%)	Kim <i>et al.</i> , 2007
	AOPs: UV+H ₂ O ₂	Deionized water	0.000218 mg/L	750 mJ/cm ² UV 10 mg/L H ₂ O ₂	90%	Lester <i>et al.</i> , 2014
		Wastewater	0.00032 mg/L	700 mJ/cm ² UV 20 mg/L H ₂ O ₂	90%	Rosario-Ortiz <i>et al.</i> , 2010
	AOPs: UV+Catalysts	Wastewater	5 mg/L	4.7×10 ⁻⁷ einstein L ⁻¹ s ⁻¹ UV Irradiation time:120 min 800 mg/L TiO ₂	85%	Rizzo <i>et al.</i> , 2009
		Wastewater	5 mg/L	TiO ₂ nanofiber, UV-254 nm, Reaction time: 4 h	78%	Chong and Jin, 2012
	AOPs: O ₃ +UV	Wastewater	0.0014 mg/L	2.6 g/h O ₃ , 15 W UV Reaction time: 3 min	97.5%	Gebhardt and Schröder, 2007
Wastewater		0.0021 mg/L	15 mg/L O ₃ , 4000 mJ/cm ² UV	100%	Ternes <i>et al.</i> , 2003	

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Carbamazepine	Ozonation	Wastewater	0.00025 mg/L	8.7 mg/L O ₃ Retention time:18 min	98%	Lei and Snyder, 2007
		Wastewater	0.0000333 mg/L	3 mg/L O ₃ Retention time:27 min	82%	Nakada <i>et al.</i> , 2007
	Adsorption: GAC	Groundwater	0.00018 mg/L	EBCT: 10 min	88%	Ternes <i>et al.</i> , 2002
		Wastewater	0.00025 mg/L	GAC type: Galgon F-400 EBCT: 15 min	80%	Yang <i>et al.</i> , 2011
	Adsorption: PAC	Wastewater	0.0012 mg/L	PAC dosage: 20 mg/L Contact time: 30 min	90%	Ruhl <i>et al.</i> , 2014
		Wastewater	0.0018 mg/L	PAC dosage: 20 mg/L Contact time: 30 min	90%	Altmann <i>et al.</i> , 2014
	Membrane filtration: RO	Wastewater	1mg/L	Membrane type: RO Flow rate: 3-4 L/min	97.6%	Gur-Reznik <i>et al.</i> , 2011
		Wastewater	0.0001 mg/L	Feed pressure: 14 bar	99.86%	Beier <i>et al.</i> , 2010
	Membrane filtration: NF	Wastewater	1 mg/L	Membrane type: NF270 Flow rate: 3-4 L/min	92%	Gur-Reznik <i>et al.</i> , 2011
		Wastewater	0.0001 mg/L	Feed pressure: 7 bar	88%	Beier <i>et al.</i> , 2010

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Diclofenac	Conventional drinking water treatments: Granular media filtration	Surface water	1 mg/L	Media: sand EBCT: 3.6 min	12%	Rigobello <i>et al.</i> , 2013
	Conventional drinking water treatments: Coagulation	Surface water	0.1 mg/L	Coagulant dosage: 5 mg/L Alum	3%	Simazaki <i>et al.</i> , 2008
	AOPs: UV+H ₂ O ₂	Wastewater	0.00008 mg/L	923 mJ/cm ² UV 7.8 mg/L H ₂ O ₂	98%	Kim <i>et al.</i> , 2009b
		Wastewater	N/A	307.5 mJ/cm ² UV 6.2 mg/L H ₂ O ₂	100%	Kim <i>et al.</i> , 2009a
	AOPs: O ₃ +UV	Wastewater	N/A	1846 mJ/cm ² UV 4 mg/L O ₃	100%	Kim <i>et al.</i> , 2009a
	Ozonation	Wastewater	N/A	6 mg/L O ₃ Contact time: 10 min	100%	Kim <i>et al.</i> , 2009a
	Adsorption: GAC	Wastewater	0.000099 mg/L	GAC type: Galgon F-400 EBCT: 15 min	90%	Yang <i>et al.</i> , 2011
		Wastewater	0.00008 mg/L	EBCT: 10 min	88%	Ternes <i>et al.</i> , 2002

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Diclofenac	Adsorption: PAC	Wastewater	0.0028 mg/L	PAC dosage: 20 mg/L Contact time: 30 min	90%	Ruhl <i>et al.</i> , 2014
		Wastewater	0.0041 mg/L	PAC dosage: 20 mg/L Contact time: 30 min	90%	Altmann <i>et al.</i> , 2014
	Membrane filtration: RO	Wastewater	0.001 mg/L	Feed pressure: 14 bar	99.86%	Beier <i>et al.</i> , 2010
		Wastewater	N/A	Membrane type: Filmtec TW30 Feed pressure, 9.5-10.2 bar	95%	Sahar <i>et al.</i> , 2011
	Membrane filtration: NF	Wastewater	0.001 mg/L	Feed pressure: 7 bar	99.74%	Beier <i>et al.</i> , 2010
		Wastewater	10 mg/L	Membrane type: NF-90	95%	María <i>et al.</i> , 2012
Erythromycin	Conventional drinking water treatments: Coagulation/ Sedimentation/Filtration	Surface water	0.000033 mg/L	N/A	85.5%	Boleda <i>et al.</i> , 2011
	Ozonation	Surface water	0.0000048 mg/L	N/A	72.9 %	Boleda <i>et al.</i> , 2011
		Ultrapure water	0.0005 mg/L	90 mg/L O ₃ Contact time: 5 min	85%	Derrouiche <i>et al.</i> , 2013
	AOPs: O ₃ +Catalysts	Ultrapure water	0.0005 mg/L	90 mg/L O ₃ Contact time: 5 min Catalyst: monoliths	100%	Derrouiche <i>et al.</i> , 2013

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Erythromycin	AOPs: UV+H ₂ O ₂	Wastewater	0.00015 mg/L	923 mJ/cm ² UV 7.8 mg/L H ₂ O ₂	97%	Kim <i>et al.</i> , 2009b
	AOPs: O ₃ +UV	Wastewater	N/A	1846 mJ/cm ² UV 4 mg/L O ₃	100%	Kim <i>et al.</i> , 2009a
	Adsorption: GAC	Wastewater	0.00027 mg/L	GAC type: Galgon F-400 EBCT: 15 min	74%	Yang <i>et al.</i> , 2011
		Surface water	0.000002 mg/L	N/A	60%	Boleda <i>et al.</i> , 2011
	Adsorption: PAC	Ultrapure water	0.000489 mg/L	PAC dosage: 24 mg/L	94.62%	Liu <i>et al.</i> , 2013
		Wastewater	N/A	PAC dosage: 1000 mg/L	97%	Serrano <i>et al.</i> , 2011
	Membrane filtration: RO	Surface water	0.000004 mg/L	N/A	75%	Boleda <i>et al.</i> , 2011
	Membrane filtration: UF	Surface water	0.0000048 mg/L	N/A	35.4%	Boleda <i>et al.</i> , 2011
		Surface water	0.000003 mg/L	Membrane type: thin film composites membrane Feed pressure: 4.45 bar	50%	Yoon <i>et al.</i> , 2006
Sulfamethoxazol	Conventional drinking water treatments: Granular media filtration	Wastewater	0.0000399 mg/L	Media: sand Flow rate: 110 m/day Retention time: 27 min	26.8%	Nakada <i>et al.</i> , 2007
	Ozonation	Wastewater	0.0000292 mg/L	3mg/L Ozone Contact time: 27 min	87.4%	Nakada <i>et al.</i> , 2007

(To be continued)

Table 5.2 A Summary of Critical Contaminant Removal Efficiencies by Various Treatment Alternatives

Critical contaminants	Treatment alternatives	Water sources	Influent concentrations	Operating conditions	Removal efficiency	References
Nonylphenol	Conventional drinking water treatments: Granular media filtration	Surface water	0.000035 mg/L	Media: sand Water velocity: 5 m/h	67.4%	Nam <i>et al.</i> , 2014
	Ozonation	Treated grey water	N/A	15 mg/L O ₃	79%	Hernández-Leal <i>et al.</i> , 2011
		Wastewater	0.0008 mg/L	15 mg/L O ₃	87%	Zhang <i>et al.</i> , 2008
	AOPs: UV+H ₂ O ₂	Distilled water	100 mg/L	1.4×10 ⁻⁵ einstein L ⁻¹ s ⁻¹ UV 340 mg/L H ₂ O ₂	100%	Karci <i>et al.</i> , 2013a
		Distilled water	50 mg/L	1.4×10 ⁻⁵ einstein L ⁻¹ s ⁻¹ UV 340 mg/L H ₂ O ₂	100%	Karci <i>et al.</i> , 2013b
	Adsorption: GAC	Drinking water	0.5 mg/L	N/A	97%	Choi <i>et al.</i> , 2005
		Treated grey water	0.000813 mg/L	N/A	90.7%	Hernández-Leal <i>et al.</i> , 2011
	Adsorption: PAC	Surface water	N/A	PAC dosage: 5 mg/L Contact time: 4 h	52%	Delgado <i>et al.</i> , 2012
	Membrane filtration: RO	Wastewater	0.000113 mg/L	N/A	96%	Al-Rifai <i>et al.</i> , 2011
		Wastewater	0.007-0.015 mg/L	N/A	99%	Garcia <i>et al.</i> , 2013

AOPs: advanced oxidation processes; EBCT: empty bed contact time; ES: effective size; GAC: granular activated carbon; MF: microfiltration; NF: nanofiltration; PAC: powdered activated carbon; RO: reverse osmosis; SAT: soil aquifer treatment; TMP: transmembrane pressure; UF: ultrafiltration; UC: uniformity coefficient; UV: ultraviolet light

5.4 Selection of Treatment Alternatives

5.4.1 Target Removal Efficiency

For each critical contaminant, appropriate treatment should be selected to reduce the contaminant concentration below the suggested water quality limits defined in Chapter 4. To ensure that the treatment option can achieve the required treatment goal, the treatment efficiency should exceed the target removal efficiency, which can be expressed as follows:

$$\text{Target removal efficiency} = \frac{\text{Max} - \text{Limit}}{\text{Max}}$$

Where Max is the maximum concentration of the critical contaminant; and Limit is the water quality limit for critical contaminant.

Based on the identified critical contaminants and their typical concentrations in treated wastewater effluent from Chapter 4, the target removal efficiency for each critical contaminant was calculated and summarized in Table 5.3. It is important to note that the target treatment efficiency of the microbial contaminants (*E. coli*, *Giardia*, *Cryptosporidium*) is calculated by the log reduction, which is a common way to evaluate the treatment for microorganisms. Through calculation, it can be seen that *E. coli* requires a minimum 3 log reduction to achieve the water quality target, while *Giardia* and *Cryptosporidium* should be removed by at least 6 logs. For most chemicals, greater than 50% removal are required. Only a few chemicals, including atrazine, diuron, and nitrilotriacetic acid (NTA), require lower removal efficiencies (around or less than 10%).

Table 5.3 Target Treatment Efficiency for Critical Contaminants

Contaminants	Maximum values in wastewater effluents ¹ (mg/L except as noted)	Suggested water quality limits ² (mg/L except as noted)	Target treatment efficiency ³
<i>E.coli</i>	280 CFU/100 mL	None detectable	≥3 log reduction
<i>Giardia</i>	1100 cysts/L	6 Log Reduction	≥6 Log Reduction
<i>Cryptosporidium</i>	160 oocysts/L	6 Log Reduction	≥6 Log Reduction
Nitrite (as nitrogen)	2.03	1	51%
Nitrate (as nitrogen)	27.9	10	64%
Total Ammonia (as nitrogen)	4.51	0.02	99%
Total Phosphorus	0.59	0.01	98%
Aluminum	0.724	0.1	86%
Manganese	0.105	0.05	52%
Chloride	388	250	36%
Atrazine	0.0056	0.005	11%
Diuron	0.153	0.15	2%
Di(2-ethyexyl)phthalate (DEHP)	0.182	0.004	97%
Nitrilotriacetic Acid (NTA)	0.41	0.4	2%
Perfluorooctane Sulfonate (PFOS)	0.000462	0.0002	57%
Perfluorooctanoate (PFOA)	0.00105	0.0004	61%
Ibuprofen	0.0082	0.000039	99%
Carbamazepine	0.0046	0.00061	86%
Diclofenac	0.00069	0.0001	85%
Erythromycin	0.002841	0.000145	94%
Sulfamethoxazol	0.00115	0.000025	97%
Nonylphenol	0.0078	0.0007	91%

1. The maximum concentrations are based on values from Table 4.6, Table 4.8, and Table 4.9 in Chapter 4.
2. The suggested water quality limits are based on values from Table 4.3 and Table 4.9 in Chapter 4.
3. The calculation of target treatment efficiency is based on the equation discussed in section 5.4.1, and is rounded to the nearest whole percentage point.

5.4.2 Assigned Treatment Efficiency Credit

The next step is to select the treatment options that can meet the contaminant removal efficiencies determined in Table 5.3. To select the best available treatment to remove each

critical contaminant, the efficiency of each treatment options is obtained from the studies included in Table 5.2. For most treatment alternatives, two studies were selected as a reference for the determination of removal efficiency ranges; however, sometimes only one study was available. When two or more studies were available, different values for the removal of critical contaminants were determined using the criteria described below (a to e). Based on these criteria, the assigned treatment efficiency credits for each alternative are summarized in Table 5.4. Feasible treatment alternatives with an assigned treatment credit larger than target treatment efficiency were bold and underlined (Table 5.4).

a) If the two studies were operated under similar conditions, and both studies had similar treatment efficiencies (e.g. the difference was less than 10 percentage points for chemicals and less than 0.5 log for microorganisms), the treatment credit was assigned based on the average of the removal efficiency of the two studies. To conservatively represent the ability of treatment alternatives, the assigned credit for log reduction was rounded down to the closest 0.5 log removal value (X.0 or X.5), and percentage removals rounded down to the closest 5% value (X0% or X5%). For example, 65% and 69% nitrate removals were achieved by ion exchange respectively in the Clifford and Liu (1993) and Richarch (1989) studies. Since the average of these values was 67%, this was rounded down to 65% in Table 5.4, which is slightly lower than their average of 67%.

b) If there was a large difference in removal efficiency between studies, this may possibly be due to different treatment conditions. In this circumstance, the operating conditions in each study were analyzed first. If only one study used conditions that would be considered normal for full-scale water treatment operations, then the data from that study was used to assign a treatment credit. For example, Shu *et al.* (2013) showed that 2,470 mJ/cm² UV and 25 mg/L H₂O₂ could remove 90% of ibuprofen from water, while Mestre *et al.* (2011) used 540 mJ/cm² UV and 6 mg/L H₂O₂ and obtained 68% removal of ibuprofen. Since the normal UV dose applied in full-scale AOPs is around 500 mJ/cm² (Monge, 2011), the Shu *et al.* (2013) study

using a very high UV dose was excluded, and the treatment credit for AOPs to remove ibuprofen was set at 68%.

c) If neither of the studies was conducted under typical full-scale operating conditions, the treatment credit was assigned based on the Health Canada and U.S. EPA technical documents for that particular treatment. For example, Bischoff *et al.* (2013) achieved 4.3 log reduction of *E.coli* in wastewater by using 15 mJ/cm² UV, while Nasser *et al.* (2006) used 20 mJ/cm² UV to obtain a 5 log inactivation of *E.coli* in wastewater. The UV dose used in the selected studies is much lower than the commonly applied UV dose of 40 mJ/cm² for water supply systems in Canada (Health Canada, 2012a). Based on the dose-response relationship between UV dose and *E.coli* shown in the *National Primary Drinking Water Regulations: Long Terms 2 Enhanced Surface Water Treatment* (U.S.EPA, 2006), approximately 6 log reduction of *E.coli* can be achieved when a 40 mJ/cm² of UV dose is applied, and therefore this value was used in Table 5.4 This approach was also applied to estimate the removal of other microorganisms such as *Giardia* and *Cryptosporidium* by UV disinfection or chemical disinfection, whose performance is largely influenced by disinfectant doses.

d) If the studies compared used different types of water sources under normal operating conditions, the treatment efficiency in the study that can better simulate a wastewater matrix was used as the treatment efficiency credit. The source water selection criterion was based on the following sequence: wastewater > treated grey water > surface water > groundwater > tap water > drinking water > model solution (i.e. deionized water, distilled water, demineralized water, ultrapure water, methanol). For example, Beier *et al.* (2010) achieved 85.71% ibuprofen removal from wastewater by a nanofiltration membrane, while 97% reduction was achieved in Botton *et al.* (2012) using tap water as the feed water. Since wastewater is essentially the wastewater reclamation treatment environment, the removal efficiency achieved in Beier *et al.* (2010) was selected.

e) If only one study was available that provided data on the removal of a specific type of contaminant, then its treatment efficiency was used as the assigned credit.

Table 5.4 Summary of Assigned Treatment Efficiency Credit for Each Treatment Alternative

Contaminant group	Critical contaminants	Treatment alternatives	Assigned treatment efficiency credit	Selection criteria or Source
Microorganisms (reduction expressed as log units)	<i>E.coli</i>	<u>UV disinfection</u>	6 log	U.S.EPA, 2006
		<u>Chemical disinfection: Chlorine</u>	4 log	Average
		<u>Chemical disinfection: Chlorine dioxide (ClO₂)</u>	4.1 log	Bischoff <i>et al.</i> , 2013
		<u>Chemical disinfection: Ozone</u>	4.5 log	Average
		<u>Membrane filtration: UF</u>	4 log	Li <i>et al.</i> , 2008
	<i>Giardia</i>	<u>UV disinfection</u>	6 log	U.S.EPA, 2006
		Chemical disinfection: Ozone	3 log	Passos <i>et al.</i> , 2014
		Granular media filtration	3 log	U.S.EPA, 2006
		Membrane filtration: UF	≥5.2 log	Jacangelo <i>et al.</i> , 1995
		Membrane filtration: MF	≥5.2 log	Jacangelo <i>et al.</i> , 1995
	<i>Cryptosporidium</i>	<u>UV disinfection</u>	6 log	U.S.EPA, 2006
		Chemical disinfection: ozone	3.5 log	Rennecker <i>et al.</i> , 1999
		Granular media filtration	3 log	U.S.EPA, 2006
		<u>Membrane filtration: MF</u>	6 log	Average
	Nutrients (N, P)	Nitrate/Nitrite	<u>Ion exchange</u>	65%
<u>Membrane filtration: NF</u>			80%	Average
<u>Membrane filtration: RO</u>			95%	Average
<u>Electrodialysis</u>			80%	Average
<u>Chemical reduction</u>			62%	Luk and Au-Yeung, 2002

(To be continued)

Table 5.4 Summary of Assigned Treatment Efficiency Credit for Each Treatment Alternative

Contaminant group	Critical contaminants	Treatment alternatives	Assigned treatment efficiency credit	Sources	
Nutrients (N, P)	Ammonia	<u>Ion exchange</u>	100%	Average	
		Membrane filtration: NF	27%	Kurama <i>et al.</i> , 2002	
		Membrane filtration: RO	95%	Average	
	Total Phosphorus	Chemical reduction	95%	Average	
		Membrane filtration: NF	95%	Average	
		Membrane filtration: UF	90%	Average	
Metals	Aluminum	<u>Ion exchange</u>	90%	Average	
		<u>Membrane filtration: RO</u>	≥90%	Srinivasan <i>et al.</i> , 1999	
		<u>Electrodialysis</u>	≥90%	Srinivasan <i>et al.</i> , 1999	
		<u>Chemical reduction</u>	97%	Nilson <i>et al.</i> , 1992	
	Manganese	<u>Oxidation</u>	71%	Zhu <i>et al.</i> , 2009	
		<u>Ion exchange</u>	99%	White and Asfar-Siddique, 1997	
		<u>Adsorption</u>	86%	Qomi <i>et al.</i> , 2014	
		<u>Membrane filtration (with oxidation)</u>	90%	Average	
	Salts	Chloride	<u>Adsorption</u>	90%	Average
			<u>Membrane filtration: RO</u>	91%	Jevtitch <i>et al.</i> , 1986
Trace organics	Atrazine	<u>AOPs: UV+H₂O₂</u>	95%	Average	
		<u>Adsorption: GAC</u>	95%	Average	
		<u>Adsorption: PAC</u>	95%	Average	
		<u>Membrane filtration: RO</u>	95%	Average	
		<u>Membrane filtration: NF</u>	75%	Average	
		<u>Membrane filtration: UF</u>	40%	Yoon <i>et al.</i> , 2006	

(To be continued)

Table 5.4 Summary of Assigned Treatment Efficiency Credit for Each Treatment Alternative

Contaminant group	Critical contaminants	Treatment alternatives	Assigned treatment efficiency credit	Sources
Trace organics	Diuron	<u>Conventional drinking water treatment: Coagulation</u>	20%	El-Dib and Aly, 1977
		<u>AOPs: UV+Fe³⁺</u>	82%	Djebbar <i>et al.</i> , 2008
		<u>AOPs: UV+Fe³⁺+H₂O₂</u>	95%	Average
		<u>Ozonation</u>	23%	Ormad <i>et al.</i> , 2010
		<u>Adsorption: GAC</u>	90%	Baup <i>et al.</i> , 2002
		<u>Adsorption: PAC</u>	95%	Baup <i>et al.</i> , 2002
		<u>Membrane filtration: NF</u>	85%	Average
		Di(2-ethylhexyl)phthalate (DEHP)	Conventional drinking water treatment: Granular media filtration	80%
	Conventional drinking water treatment: Coagulation		56%	Theepharaksapan <i>et al.</i> , 2011
	AOPs: H ₂ O ₂ +Fe ²⁺		85%	Esmaeli <i>et al.</i> , 2011
	AOPs: UV+H ₂ O ₂		70%	Park and Kim, 2012
	AOPs: O ₃ +Catalysts		75%	Hammad Khan and Jung, 2008
	Ozonation		80%	Zheng <i>et al.</i> , 2014
	Membrane filtration: NF		90%	Shen <i>et al.</i> , 2014
	Nitrilotriacetic Acid (NTA)	<u>Ozonation</u>	75%	Games and Staubach, 1980
Perfluorooctane Sulfonate (PFOS)	Conventional drinking water treatment: Coagulation	6.6%	Xiao <i>et al.</i> , 2013	
	<u>Adsorption: GAC</u>	65%	Average	
	<u>Adsorption: PAC</u>	90%	Average	

(To be continued)

Table 5.4 Summary of Assigned Treatment Efficiency Credit for Each Treatment Alternative

Contaminant group	Critical contaminants	Treatment alternatives	Assigned treatment efficiency credit	Sources
Trace organics	Perfluorooctane Sulfonate (PFOS)	<u>Membrane filtration: RO</u>	95%	Average
		<u>Membrane filtration: NF</u>	95%	Average
	Perfluorooctanoate (PFOA)	Conventional drinking water treatment: Coagulation	-0.6% (0%)	Xiao <i>et al.</i> , 2013
		Adsorption: GAC	45%	Average
		<u>Adsorption: PAC</u>	85%	Average
		<u>Membrane filtration: RO</u>	97%	Thompson <i>et al.</i> , 2011
		<u>Membrane filtration: NF</u>	95%	Average
	Ibuprofen	Conventional drinking water treatments: Coagulation	-16% (0%)	Kim <i>et al.</i> , 2007
		Ozonation	77%	Huber <i>et al.</i> , 2003
		AOPs: O ₃ +H ₂ O ₂	95%	Average
		AOPs: UV+H ₂ O ₂	68%	Kruithof and Martijn, 2013
		Adsorption: GAC	70%	Baccar <i>et al.</i> , 2012
		Adsorption: PAC	90%	Average
		Membrane filtration: NF	86%	Beier <i>et al.</i> , 2010
	Carbamazepine	Conventional drinking water treatments: Coagulation	-9% (0%)	Kim <i>et al.</i> , 2007
		<u>AOPs: UV+H₂O₂</u>	90%	Average
		AOPs: UV+Catalysts	80%	Average
		<u>AOPs: O₃+UV</u>	95%	Average
		Ozonation	82%	Nakada <i>et al.</i> , 2007
		Adsorption: GAC	80%	Average
	<u>Adsorption: PAC</u>	90%	Average	

(To be continued)

Table 5.4 Summary of Assigned Treatment Efficiency Credit for Each Treatment Alternative

Contaminant group	Critical contaminants	Treatment alternatives	Assigned treatment efficiency credit	Sources
Trace organics	Carbamazepine	<u>Membrane filtration:</u> <u>RO</u>	95%	Average
		<u>Membrane filtration: NF</u>	90%	Average
	Diclofenac	Conventional drinking water treatments: Granular media filtration	12%	Rigobello <i>et al.</i> , 2013
		Conventional drinking water treatments: Coagulation	3%	Simazaki <i>et al.</i> , 2008
		<u>AOPs: UV+H₂O₂</u>	95%	Average
		<u>AOPs: O₃+UV</u>	100%	Kim <i>et al.</i> , 2009a
		<u>Ozonation</u>	100%	Kim <i>et al.</i> , 2009a
		<u>Adsorption: GAC</u>	90%	Average
		<u>Adsorption: PAC</u>	90%	Average
		<u>Membrane filtration:</u> <u>RO</u>	95%	Average
		<u>Membrane filtration: NF</u>	95%	Average
		Erythromycin	Conventional drinking water treatments: Coagulation/ Sedimentation/Filtration	85%
	Ozonation		73%	Boleda <i>et al.</i> , 2011
	<u>AOPs: O₃+Catalysts</u>		100%	Derrouiche <i>et al.</i> , 2013
	<u>AOPs: UV+H₂O₂</u>		97%	Kim <i>et al.</i> , 2009b
	<u>AOPs: O₃+UV</u>		100%	Kim <i>et al.</i> , 2009a
	Adsorption: GAC		74%	Yang <i>et al.</i> , 2011
	<u>Adsorption: PAC</u>		97%	Average
	Membrane filtration: RO		75%	Boleda <i>et al.</i> , 2011
	Membrane filtration: UF		40%	Average

(To be continued)

Table 5.4 Summary of Assigned Treatment Efficiency Credit for Each Treatment Alternative

Contaminant group	Critical contaminants	Treatment alternatives	Assigned treatment efficiency credit	Sources
Trace organics	Sulfamethoxazol	Conventional drinking water treatments: Granular media filtration	27%	Nakada <i>et al.</i> , 2007
		Ozonation	87%	Nakada <i>et al.</i> , 2007
	Nonylphenol	Conventional drinking water treatments: Granular media filtration	68%	Nam <i>et al.</i> , 2014
		Ozonation	85%	Average
		<u>AOPs: UV+H₂O₂</u>	100%	Average
		<u>Adsorption: GAC</u>	90%	Average
		Adsorption: PAC	52%	Delgado <i>et al.</i> , 2012
		<u>Membrane filtration:</u> <u>RO</u>	95%	Average

5.4.3 Potential Treatment Alternatives

By comparing the assigned treatment alternative efficiencies (Table 5.4) and target treatment efficiencies for each critical contaminant (Table 5.3), treatment alternatives whose assigned treatment credit is larger than the target treatment efficiency were identified (bold and underlined in Table 5.4). For some critical contaminants including total phosphorus, DEHP, ibuprofen, and sulfamethoxazol, none of the individual treatment units included in Table 5.2 was found to ensure that the concentration reduction met the defined water treatment targets. There may be several reasons accounting for this result. First, previous studies may not provide accurate or enough data to show the ability of a treatment alternative to remove particular contaminants. Therefore, the current available studies should be thoroughly analyzed to provide reasonable suggestions for treatment options. For example, Jacangelo *et al.* (1995) found that *Giardia* was reduced by at least 5.2 log using a UF membrane. However, the actual removal is likely higher, but 5.2 log was the *Giardia* concentration in the influent water. Since a 6 log reduction of *Cryptosporidium*, which has a size smaller than *Giardia*,

was achieved by both Lovins III *et al.* (2002) and States *et al.* (2000) using a larger pore size MF membrane, a 6 log removal credit was assigned for both MF and UF membranes to remove *Cryptosporidium* and *Giardia*. In this case, it can be deduced that NF and RO membranes, which have a smaller pore size, could also effectively remove these two types of protozoa. As another example, only one study conducted by Nakada *et al.* (2007) was found to investigate the removal of sulfamethoxazol by granular media filtration and ozonation. Based on the currently available data, although ozonation's credit is smaller than the treatment target, this treatment may still reduce sulfamethoxazol concentration in wastewater effluent to below the limit when its concentration is not very high in most cases. Since AOPs were found to be more effective for the direct mineralization of trace organics than ozonation (Ito *et al.*, 1998), AOPs were also proposed as potential treatments for sulfamethoxazol.

The second consideration in choosing potential treatment options is that the target treatment efficiency is set based on the maximum concentration of contaminants reported in wastewater effluents, and this may be too stringent for the selection of treatment alternatives. Some treatment alternatives may be capable of removing critical contaminants to the desired value within the normal contaminant concentration range, but not at the maximum values. For example, the rejection of DEHP by a NF membrane was reported as 90% (Shen *et al.*, 2014), which is slightly lower than the required target removal efficiency for DEHP (97%). It can be deduced that an NF membrane may effectively reduce DEHP concentration under most conditions, but that an RO membrane would be required to effectively treat the maximum concentration.

Table 5.5 shows a list of potential treatments that were able to meet the removal targets for each critical contaminant. To reduce the uncertainties discussed above, treatment alternatives that could meet the required treatment efficiency within 10 percentage points (chemicals) or 0.5 log (microorganisms) were also selected as potential treatment alternative candidates. In terms of microbial critical contaminants, the *E.coli* concentration can be reduced to below the water quality limit by all the water treatment alternatives listed in Table

5.4. Since UF membranes were found to effectively remove *E.coli*, tighter membranes such as NF and RO can also be selected. For both *Giardia* and *Cryptosporidium*, UV disinfection is selected as a potential treatment unit since its treatment credit can meet the target. As discussed in the previous paragraph, membrane filtration can be also selected as a potential treatment to remove both *Giardia* and *Cryptosporidium*. Even though chemical disinfection can effectively inactivate bacteria such as *E.coli*, it may not be efficient for the removal of protozoa, which are much more resistant to chemical disinfectants, under normal operating conditions. Therefore, chemical disinfection was not selected. Based on the discussion above, UV disinfection and membrane filtration (UF/NF/RO) were identified as the best treatment choices for the removal of all microbial contaminants.

Table 5.5 Potential Treatment Alternatives for Critical Contaminants

Contaminant group	Critical contaminants	Potential treatment alternatives
Microorganisms	<i>E.coli</i>	UV disinfection, Membrane filtration (UF/NF/RO), Chemical disinfection (Chlorine/Chloride dioxide/Ozone)
	<i>Giardia</i>	UV disinfection, Membrane filtration (MF/UF/NF/RO)
	<i>Cryptosporidium</i>	UV disinfection, Membrane filtration (MF/UF/NF/RO)
Nutrients (N, P)	Nitrate/Nitrite	Ion exchange, Membrane filtration (NF/RO), Electrodialysis, Chemical reduction
	Ammonia	Ion exchange, Membrane filtration (RO)
	Total Phosphorus	Chemical reduction, Membrane filtration (NF/RO)
Metals	Aluminum	Ion exchange, Membrane filtration (RO), Electrodialysis, Chemical reduction
	Manganese	Oxidation, Ion exchange, Adsorption, Membrane filtration (with oxidation)
Salts	Chloride	Adsorption, Membrane filtration (RO)
Trace organics	Atrazine	AOPs (UV+H ₂ O ₂), Adsorption (GAC/PAC), Membrane filtration (UF/NF/RO)
	Diuron	Conventional drinking water treatment (Coagulation), AOPs (UV+Fe ³⁺ , UV+Fe ³⁺ +H ₂ O ₂), Ozonation, Adsorption (GAC/PAC), Membrane filtration (NF/RO)
	Di(2-ethylhexyl)phthalate (DEHP)	Membrane filtration (NF/RO)

(To be continued)

Table 5.5 Potential Treatment Alternatives for Critical Contaminants

Contaminant group	Critical contaminants	Potential treatment alternatives
Trace organics	Nitrilotriacetic Acid (NTA)	Ozonation, AOPs
	Perfluorooctane Sulfonate (PFOS)	Adsorption (GAC/PAC), Membrane filtration (NF/RO)
	Perfluorooctanoate (PFOA)	Adsorption (PAC), Membrane filtration (NF/RO)
	Ibuprofen	AOPs (O ₃ +H ₂ O ₂), Adsorption (PAC)
	Carbamazepine	AOPs (UV+H ₂ O ₂ , UV+Catalysts, O ₃ +UV), Ozonation, Adsorption (GAC/PAC), Membrane filtration (NF/RO)
	Diclofenac	AOPs (UV+H ₂ O ₂ , O ₃ +UV), Ozonation, Adsorption (GAC/PAC), Membrane filtration (NF/RO)
	Erythromycin	AOPs (O ₃ +Catalysts, UV+H ₂ O ₂ , O ₃ +UV), Adsorption (PAC)
	Sulfamethoxazol	Ozonation, AOPs
	Nonylphenol	AOPs (UV+H ₂ O ₂), Ozonation, Adsorption (GAC), Membrane filtration (RO)

AOPs: Advanced Oxidation Processes; GAC: Granular Activated Carbon; NF: Nanofiltration; PAC: Powdered Activated Carbon; RO: Reverse Osmosis; UF: Ultrafiltration; UV: Ultraviolet

In terms of nutrients, upgraded treatment processes in WWTPs can lower nitrogen and phosphorus levels in wastewater. For wastewater reclamation, ion exchange and RO were both identified as potential treatment alternatives for the removal of nitrogen compounds such as nitrate, nitrite, and ammonia. For phosphorus removal, it was found that NF membranes can reduce the phosphorus level to below the water quality limit based on the studies conducted by Acero *et al.* (2010) and dos Santos *et al.* (2014). Therefore, it can be deduced that RO membranes, which have a smaller pore size, can achieve a similar or higher phosphorus rejection. As a cost-effective treatment option, chemical reduction has been assigned a 95% phosphorus removal credit, which is just a little lower than the treatment target (98%). Hence, chemical reduction is also selected for the removal of phosphorus. Based on the discussion above, RO was identified having the best treatment performance for the overall removal of nitrogen and phosphorus nutrients.

For metals, all the treatment alternatives listed in Table 5.4 are able to reduce aluminum and manganese concentrations to below the limits. Since ion exchange can remove a large amount of aluminum and manganese, this technology was selected as the most promising treatment candidate for the removal of metals. In terms of salt rejection, adsorption and RO listed in Table 5.4 are both the feasible choices.

In terms of trace organics, all the proposed treatment alternatives listed in the Table 5.4 were found to effectively remove the herbicides atrazine and diuron. The maximum concentrations of both contaminants in wastewater effluents are not much larger than the water quality limits, and hence target treatment efficiencies for these two herbicides are not high and all the proposed treatment alternatives can reach the targets. For DEHP, both NF and RO membranes can reduce the concentration of this chemical to below the water quality limit in most cases. Ozonation was found to be effective to remove NTA. As discussed above, AOPs normally can be more effective for the mineralization of trace organics than ozonation, and therefore were also proposed as potential treatments. For PFCs including PFOS and PFOA, PAC adsorption and high pressure membrane filtration (RO/NF) were both found to be effective ways for the removal of both chemicals. For pharmaceuticals, AOPs and PAC adsorption were selected as the potential treatment choices for removal of all three chemicals (ibuprofen, carbamazepine, diclofenac). For antibiotics, AOPs were expected to have the most potential as a treatment option. For personal care products, AOPs, ozonation, GAC adsorption, and RO were proposed as potential choices for the removal of nonylphenol. Based on the discussion above, AOPs, adsorption (PAC/GAC), and high pressure membrane filtration (NF/RO) are identified as the most potential treatments for the removal of trace organics.

5.4.4 Potential Treatment Trains

Table 5.6 shows the summary of potential alternatives to remove critical contaminants based on Table 5.5 as discussed in the previous paragraph. It can be seen that not a single treatment alternative is able to effectively remove all 22 critical contaminants. To produce high quality

recharge water, different treatment alternatives should be combined to form the required treatment trains. From a system perspective, treatment alternatives which can remove a broader range of critical contaminants are favored since they can reduce the redundancy of similar treatment units in one treatment train and increase the robustness of treatment systems.

As shown in Table 5.6, NF and RO are the treatments which can remove the majority of critical contaminants, and therefore one of them should be included in the potential treatment train. Since high pressure membranes are quite susceptible to membrane fouling (Shon *et al.*, 2005; Shang *et al.*, 2011), additional pretreatment should be applied prior to NF or RO. Among the potential treatment alternatives listed in Table 5.6, MF and UF are the most suitable options since they can effectively remove suspended solids and colloidal materials, which can greatly contribute to the fouling of high pressure membranes. In addition, UF membranes have a smaller pore size than MF membranes, and can remove more critical contaminants such as *E. coli* and atrazine, thus increasing the robustness of the treatment system. Hence, it is recommended that UF should be included in the treatment trains, although some pre-treatment to remove particulates and organics may need to be included prior to the UF. For sulfamethoxazol, AOPs and ozonation were found to be the only potential treatment options based on the previous studies, and therefore the potential treatment train should also include either of these two treatment choices. According to the discussion in Section 5.3, UV-based AOPs are quite effective for the removal of trace organics. Since UV light can also effectively disinfect the microbial contaminants in wastewater effluents, it is better to include UV-based AOPs in the treatment train.

Table 5.6 Summary of Potential Treatment Alternatives for the Removal of Critical Contaminants

Critical contaminants	UV	CD	MF	UF	NF	RO	ED	CR	OD	OZ	IX	GAC	PAC	AD	AOPs	CDWT
<i>E.coli</i>																
<i>Giardia</i>																
<i>Cryptosporidium</i>																
Nitrate/Nitrite																
Ammonia																
Total Phosphorus																
Aluminum																
Manganese			1	1	1	1										
Chloride																
Atrazine																
Diuron																
Di(2-ethylhexyl)phthalate (DEHP)																
Nitrilotriacetic Acid (NTA)																
Perfluorooctane Sulfonate (PFOS)																
Perfluorooctanoate (PFOA)																

(To be continued)

Table 5.6 Summary of Potential Treatment Alternatives for the Removal of Critical Contaminants

Critical contaminants	UV	CD	MF	UF	NF	RO	ED	CR	OD	OZ	IX	GAC	PAC	AD	AOPs	CDWT
Ibuprofen																
Carbamazepine																
Diclofenac																
Erythromycin																
Sulfamethoxazol																
Nonylphenol																

1. Membrane filtration (MF/UF/NF/RO) may be effective for the removal of manganese but should be combined with oxidation processes.

AD: adsorption; AOPs: advanced oxidation processes; CD: chemical disinfection; CDWT: conventional drinking water treatments; CR: chemical reduction; ED: electro dialysis; GAC: granular activated carbon adsorption; IX: ion exchange; MF: microfiltration; NF: nanofiltration; OD: oxidation; OZ: ozonation; PAC: powdered activated carbon adsorption; RO: reverse osmosis; UF: ultrafiltration; UV: ultraviolet disinfection

Based on the discussion above, NF or RO, UF, and UV-based AOPs are the essential treatment units that should be included in the treatment train. If NF is selected as a treatment unit, two contaminants, including aluminum and chloride, may not be effectively treated. To deal with these chemicals, other treatment units would have to be included. From Table 5.6, it can be seen that three types of treatment combination (adsorption + ion exchange, adsorption + electro dialysis, adsorption + chemical reduction) are capable of reducing the concentration of these two substances to below the water quality limits. Since ion exchange was shown to effectively remove more contaminants than electro dialysis and chemical reduction, the combination of nanofiltration together with adsorption and ion exchange is favored in terms of system robustness. Alternatively, if RO is selected, three essential treatment units can effectively remove all critical contaminants. The two treatment train options discussed above are shown in Table 5.7.

Table 5.7 Potential Treatment Trains for the Removal of Critical Contaminants

No.	Treatment train
1	Adsorption + Ion exchange + Ultrafiltration + Nanofiltration + UV-based AOPs
2	Ultrafiltration + Reverse Osmosis + UV-based AOPs

5.4.5 Performance Evaluation of Potential Treatment Trains

Based on the assigned credits for the removal of critical contaminants by each treatment alternative in Table 5.4, the overall removal efficiency by the potential treatment trains can each be determined for each contaminant. However, due to a lack of studies, data on contaminant removal by some treatment processes is not available. For example, RO does not have an assigned credit for the removal of *E. coli*, even though it would be expected to substantially reduce the concentration of *E. coli* in water. In this situation, the treatment unit can be conservatively assigned a minimum credit based on the assigned credit of other similar types of treatment. The process of assigning the minimum credit is based on the following assumptions:

- 1) Membranes which have a smaller pore size will have equal or higher removal efficiency of certain contaminants. For instance, it can be assumed that RO membranes can achieve at least 4 log reduction of *E. coli* since UF membranes have a 4 log reduction credit for *E. coli*.
- 2) AOPs will have a higher removal efficiency of certain contaminants than ozonation or ordinary oxidation processes. For instance, AOPs can be assigned with at least 71% for manganese removal since normal oxidation has been assigned with a 71% removal credit for manganese based on previous studies. This approach would also be appropriate in general because, for a given contaminant, removal by an AOP would only be higher than removal by ozonation if the contaminant were oxidized primarily by hydroxyl radicals instead of by molecular ozone.

Based on credit assigned to each treatment unit for the removal of certain contaminants, the recommended treatment train's removal efficiency for each critical contaminant (shown in Table 5.8 and Table 5.9) can be calculated as follows:

$$R_o = 1 - \prod_{i=1}^n (1 - r_i)$$

Where R_o is the overall treatment efficiency of the treatment train for a specific contaminant, r_i is the treatment efficiency of i^{th} treatment alternative, n is the number of treatment alternatives in the treatment train. By using this approach, it is assumed that the percentage removals reported previously for a process will remain the same even if a prior process in the treatment train has already removed some of the contaminant. Although the contaminant influent concentration may influence the treatment performance, it would be too complicated to consider this impact when evaluating the efficiency of treatment trains. Therefore, the calculation of treatment train efficiency should be based on the assumptions discussed above.

The removal efficiency of each critical contaminant by No.1 treatment train is shown in Table 5.8, while Table 5.9 shows the efficiency of No.2 treatment train.

Table 5.8 Removal Efficiency of Each Critical Contaminant by No.1 Treatment Train

Critical contaminants	AD	IX	UF	NF	UV-based AOPs	Overall treatment efficiency	Target Treatment Efficiency
<i>E. coli</i>	N/A ¹	N/A ¹	4 log reduction	≥4 log reduction	6 log reduction	≥14 log reduction	≥3 log reduction
<i>Giardia</i>	N/A ¹	N/A ¹	≥5.2 log reduction	≥5.2 log reduction	6 log reduction	≥16.4 log reduction	≥6 log reduction
<i>Cryptosporidium</i>	N/A ¹	N/A ¹	≥6 log reduction	≥6 log reduction	6 log reduction	≥18 log reduction	≥6 log reduction
Nitrate/Nitrite	N/A ¹	65%	N/A ¹	80%	N/A ¹	93%	64%/51%
Ammonia	N/A ¹	100%	N/A ¹	27%	N/A ¹	100%	99%
Total Phosphorus	N/A ¹	N/A ¹	90%	95%	N/A ¹	99%	98%
Aluminum	N/A ¹	90%	N/A ¹	N/A ¹	N/A ¹	90%	86%
Manganese	86%	99%	≥90%	≥90%	≥71%	≥99%	52%
Chloride	90%	N/A ¹	N/A ¹	N/A ¹	N/A ¹	90%	36%
Atrazine	N/A ¹	N/A ¹	40%	75%	95%	99%	10%
Diuron	N/A ¹	N/A ¹	N/A ¹	85%	≥82%	≥97%	2%
DEHP	N/A ¹	N/A ¹	N/A ¹	90%	70%	97%	97%
NTA	N/A ¹	N/A ¹	N/A ¹	N/A ¹	≥75%	≥75%	2%
PFOS	N/A ¹	N/A ¹	N/A ¹	95%	N/A ¹	95%	57%
PFOA	N/A ¹	N/A ¹	N/A ¹	95%	N/A ¹	95%	61%
Ibuprofen	N/A ¹	N/A ¹	N/A ¹	86%	68%	<u>95%</u>	99%
Carbamazepine	N/A ¹	N/A ¹	N/A ¹	90%	≥80%	≥98%	86%
Diclofenac	N/A ¹	N/A ¹	N/A ¹	95%	≥95%	≥99%	85%
Erythromycin	N/A ¹	N/A ¹	40%	≥40%	≥97%	≥99%	94%
Sulfamethoxazol	N/A ¹	N/A ¹	N/A ¹	N/A ¹	≥87%	<u>≥87%</u>	97%
Nonylphenol	N/A ¹	N/A ¹	N/A ¹	N/A ¹	100%	100%	91%

1. No available data for this treatment

AD: Adsorption; DEHP: Di(2-ethylhexyl)phthalate; IX: Ion exchange; NF: Nanofiltration;
 NTA: Nitrilotriacetic Acid; PFOA: Perfluorooctanoate; PFOS: Perfluorooctane Sulfonate;
 UF: Ultrafiltration; UV: Ultraviolet

Table 5.9 Removal Efficiency of Each Critical Contaminant by No.2 Treatment Train

Critical contaminants	UF	RO	UV-based AOPs	Overall treatment efficiency	Target Treatment Efficiency
<i>E. coli</i>	4 log reduction	≥4 log reduction	6 log reduction	≥14 log reduction	≥3 log reduction
<i>Giardia</i>	≥5.2 log reduction	≥5.2 log reduction	6 log reduction	≥16.4 log reduction	≥6 log reduction
<i>Cryptosporidium</i>	≥6 log reduction	≥6 log reduction	6 log reduction	≥18 log reduction	≥6 log reduction
Nitrate/Nitrite	N/A ¹	95%	N/A ¹	95%	64%/51%
Ammonia	N/A ¹	95%	N/A ¹	95%	99%
Total Phosphorus	90%	≥95%	N/A ¹	≥99%	98%
Aluminum	N/A ¹	≥90%	N/A ¹	≥90%	86%
Manganese	≥90%	≥90%	≥71%	≥99%	52%
Chloride	N/A ¹	91%	N/A ¹	91%	36%
Atrazine	40%	95%	95%	99%	10%
Diuron	N/A ¹	≥85%	≥82%	≥97%	2%
DEHP	N/A ¹	≥90%	70%	≥97%	97%
NTA	N/A ¹	N/A ¹	≥75%	≥75%	2%
PFOS	N/A ¹	95%	N/A ¹	95%	57%
PFOA	N/A ¹	97%	N/A ¹	97%	61%
Ibuprofen	N/A ¹	≥86%	68%	≥95%	99%
Carbamazepine	N/A ¹	95%	≥80%	≥99%	86%
Diclofenac	N/A ¹	95%	≥95%	≥99%	85%
Erythromycin	40%	75%	≥97%	≥99%	94%
Sulfamethoxazol	N/A ¹	N/A ¹	≥87%	≥87%	97%
Nonylphenol	N/A ¹	95%	100%	100%	91%

1. No available data for this treatment

DEHP: Di(2-ethylhexyl)phthalate; NTA: Nitritotriacetic Acid; PFOA: Perfluorooctanoate; PFOS: Perfluorooctane Sulfonate; RO: Reverse osmosis; UF: Ultrafiltration; UV: Ultraviolet

In Table 5.8, it can be seen that No.1 treatment train could meet or exceed the target treatment efficiency for most critical contaminants except for ibuprofen and sulfamethoxazol (highlighted in Table 5.8). As shown in Table 5.9, No.2 treatment train is also effective for the removal of most critical contaminants. Again, the concentrations of ibuprofen and

sulfamethoxazol (highlighted in Table 5.9) in wastewater effluents may not be reduced to reach the water targets by the treatment train. It may be that the defined target treatment efficiencies for both contaminants in Table 5.3 are too high so that none of treatment train could meet the targets. Another reason may be that the number of studies which investigated these chemicals is limited, and further research may show that these contaminants could be removed under optimal conditions. However, removal efficiencies of ibuprofen and sulfamethoxazol could both meet the treatment targets within 10%. Therefore, both tables can demonstrate the high effectiveness of these two treatment trains.

Table 5.10 compares the efficiency of both treatment trains for the removal of critical contaminants. In terms of microorganisms, both treatment trains can achieve an excellent performance, achieving over 14 log reduction for all three critical microbial contaminants. In terms of nutrients, No.2 treatment train may perform better than No.1 treatment train for the removal of nitrate, nitrite, and total phosphorus. However, for the ammonia removal, No.1 treatment train is found to be more effective since the ion exchange process included in the No.1 treatment train can achieve complete removal of ammonia from water, as reported in the previous studies. In terms of metals, both treatment trains have a similar efficiency for aluminum and manganese. For salt rejection, No.2 treatment train can remove more chloride than No.1 treatment train. This may be due to the reverse osmosis step included in the No.2 train, which normally achieves a higher salt rejection than the adsorption process. Adsorption required a special material as the adsorbent to reject chloride. In terms of trace organics, both treatment trains have the same removal efficiency for most contaminants. Only for PFOA and carbamazepine, No.2 train showed better performance.

Table 5.10 Treatment Performance Comparison between No.1 and No.2 treatment trains

Contaminant category	Critical contaminants	No.1 Treatment train efficiency	No.2 Treatment train efficiency	Target Treatment Efficiency
Microorganisms	<i>E. coli</i>	≥14 log reduction	≥14 log reduction	≥3 log reduction
	<i>Giardia</i>	≥16.2 log reduction	≥16.4 log reduction	≥6 log reduction
	<i>Cryptosporidium</i>	≥18 log reduction	≥18 log reduction	≥6 log reduction
Nutrients	Nitrate/Nitrite	93%	95%	64%/51%
	Ammonia	100%	95%	99%
	Total Phosphorus	99%	≥99%	98%
Metals	Aluminum	90%	≥90%	86%
	Manganese	≥99%	≥99%	52%
Salts	Chloride	90%	91%	36%
Trace organics	Atrazine	99%	99%	10%
	Diuron	≥97%	≥97%	2%
	DEHP	97%	≥97%	97%
	NTA	≥75%	≥75%	2%
	PFOS	95%	95%	57%
	PFOA	95%	97%	61%
	Ibuprofen	95%	≥95%	99%
	Carbamazepine	≥98%	≥99%	86%
	Diclofenac	≥99%	≥99%	85%
	Erythromycin	≥99%	≥99%	94%
	Sulfamethoxazol	≥87%	≥87%	97%
	Nonylphenol	100%	100%	91%

5.4.6 Preliminary Cost Evaluation of Potential Treatment Trains

Treatment costs include both capital and operating expenses. The determination of treatment costs is often dependent on the complexity of the treatments or controlling measures. A wide range of factors, including life expectancy of the plant, plant throughput, chemicals and

electricity, civil and mechanical works, and local costs for labor, should be considered. Therefore, it is quite difficult to provide a quantitative evaluation for the treatment costs (WHO, 2008).

To evaluate the treatment costs, WHO proposed a qualitative ranking system for treatment processes based on their technical complexity in terms of operation, which is shown in Table 5.11. The higher ranking means more complexity and higher costs (WHO, 2008). Since the capital, operation, and maintenance costs of adsorption processes are similar to those of granular activated carbon treatment, adsorption processes should be ranked as 4. The WHO ranked MF, UF, NF, and RO all as membrane treatments, and gave them a rank of 6. However, the infrastructure and operation costs for these four types of membrane filtration are not the same. For example, MF membranes, which have the largest pore size, would have fewer costs than finer membranes since MF materials are cheaper and its energy costs are lower due to the lower feed pressure. To distinguish their cost differences, MF is assigned a score of 6.0, while the scores of UF, NF, and RO are respectively assigned to be 6.25, 6.5, and 6.75.

Table 5.11 Ranking of Complexity and Cost of Water Treatment Processes (Adapted from WHO, 2008)

Ranking	Treatment processes
1	Simple chlorination, plain filtration (rapid sand, slow sand)
2	Pre-chlorination plus filtration, aeration
3	Process optimization for control of DBPs
4	Granular activated carbon (GAC/PAC) treatment, adsorption, ion exchange
5	Ozonation
6	Advanced oxidation processes, membrane treatment (MF: 6.0 UF: 6.25; NF: 6.5; RO: 6.75)

GAC: Granular activated carbon; MF: Microfiltration; NF: Nanofiltration

PAC: Powdered activated carbon; RO: Reverse osmosis; UF: Ultrafiltration

Based on the ranking in Table 5.11, each treatment alternative in the potential treatment trains can be assigned a cost score. The cost of each treatment train can be represented by the summation of each treatment alternative's cost score. Through calculation, the No.1 treatment train has been assigned a score of 26.75, while the No.2 treatment has a score of 19. Therefore, it can be concluded that the No.2 treatment train (Ultrafiltration + Reverse Osmosis + UV-based AOPs) is more cost-effective for the pre-treatment of MAR with reclaimed water. However, it should be noted that this is only a preliminary evaluation, and that much further work would be required before final decisions could be made.

Compared with the normal treatment trains (MF/UF + RO + AOPs/UV disinfection) which have been used to reclaim wastewater for potable reuse in previous MAR studies (Table 2.3), this treatment train also includes three advanced treatment processes, which can remove a wide range of contaminants. In the latest groundwater replenishment regulation, the California Department of Public Health defined a term "full advanced treatment" (FAT), which encompasses membrane filtration such as microfiltration (MF) and RO as well as AOPs (California Department of Public Health, 2014). It can be seen that the recommended treatment train in the current study is quite similar with this "full advanced treatment" (FAT).

5.5 Conclusions

Water pre-treatment for MAR with reclaimed water is important for the removal (i.e. reduction in concentration) of residual contaminants in wastewater effluents. Different types of water treatment technologies, including conventional wastewater treatment, conventional and advanced drinking water treatments, and advanced oxidation processes, can be helpful to remove critical contaminants for MAR with reclaimed water. Based on the types of critical contaminants, different treatment alternatives can be proposed and evaluated based on literature data from previous studies. The feasible treatment train for the pre-treatment of MAR with reclaimed water can be recommended. According to the results of this chapter, the following conclusions can be drawn:

- Different types of treatment alternatives can be proposed according to the categories of critical contaminants for MAR with reclaimed water.
- The removal of critical contaminants by the proposed treatment alternatives can be studied and evaluated based on data available in published studies. Based on these data, a treatment efficiency value can be assigned to each treatment option.
- Potential treatment trains can be proposed by comparing contaminant removals through a combination of different treatment units.
- Based on an evaluation of removal efficiencies and costs, the feasible treatment train for the pretreatment of MAR with reclaimed water was determined to be “ultrafiltration+reverse osmosis+UV-based AOPs”.

While based on an extensive evaluation of literature data, the recommended treatment train is by nature a preliminary conclusion. This recommendation provides the basis for substantial additional work, likely including pilot studies, which would need to be conducted if a decision were made to proceed with MAR.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

In this study, an initial feasibility investigation of MAR with reclaimed water in collaboration with the Region of Halton was conducted. Initially, a review of currently available water reuse regulations/guidelines was conducted since there are no federal or provincial regulations available to guide MAR projects in Ontario. Based on this review, a regulatory framework for MAR with reclaimed water was proposed. In this context, various existing MAR projects were analyzed. Next, the water quality targets for recharge water were defined based on Ontario drinking water regulations and worldwide MAR regulations/guidelines. Statistical analysis of WWTP effluent parameters using case study data identified contaminants that would require further treatment. However, because many drinking water contaminants are not regulated in WWTP effluents, data for many of the contaminants specified in the drinking water regulations had to rely on literature data. To assist with this process, representative critical contaminants were selected based on their occurrence and removal in wastewater treatment processes. Various water pre-treatment technologies to remove critical contaminants were proposed and evaluated. Potential water pre-treatment processes for MAR with reclaimed water was selected and combined to form treatment train alternatives. Based on an assessment of the overall contaminant removal efficiencies and a preliminary cost evaluation, a preferred water pre-treatment scenario was proposed. This selection provides the basis for further detailed investigations that would be required as part of a decision to implement MAR. Conclusions drawn according to the results of Chapters 2, 4, and 5 of this thesis can be summarized below.

6.1.1 Conclusions from the Review of Current Water Reuse Regulations/Guidelines and MAR Case Studies

MAR with reclaimed water is a very beneficial water reuse application but has a wide range of challenges for its implementation. Diverse aspects including planning, technical design or operational considerations, and political issues should be considered. To date, a number of water reuse regulations or guidelines have been established worldwide and some of them include requirements to govern the implementation of MAR projects. Many countries such as USA, Australia, Belgium, Israel, and China have established MAR with reclaimed water projects. Suggestions or lessons learned from current water reuse regulations/guidelines and MAR case studies are as follows:

- Five components (sources of recharge water, recharge methods, recharge sites, water treatments, and ultimate uses of recovered water) were defined and should be used to assess MAR systems. Water quality is an essential consideration and influences the key factors for MAR systems.
- A regulatory framework for MAR with reclaimed water, including planning, design, and operation, was established based on the current regulations/guidelines for MAR.
- Several established MAR with reclaimed water projects can serve as a reference for the future implementation of MAR projects. Their planning, designing, and management experience is of great importance for the success of the future MAR projects.
- Specific regulatory or design criteria for the establishment of MAR systems and a complete quantitative risk assessment framework for the evaluation and operation of MAR systems should be established in the future.

6.1.2 Conclusions for the Identification of Critical Contaminants for MAR with Reclaimed Water

Critical contaminants for MAR with reclaimed water in Canada are difficult to identify due to the lack of MAR regulatory documents. As well, there is seldom monitoring data of specific

microbial and organic contaminants that are important for indirect potable reuse, since these chemicals are not regulated in WWTP effluents. To solve the problem, a list of recharge water parameter limits for MAR was defined based on Ontario drinking water regulations and current worldwide MAR regulatory documents, and a multi-criteria approach to select critical contaminants for MAR was developed. Predominant contaminants, potential microbial and organic contaminants, and potential emerging contaminants, which together comprise critical contaminants for MAR with reclaimed water, were determined based on WWTP effluent monitoring data and literature data. WWTP data based on a conventional tertiary treatment were used as a specific example in this study, but the approach used could be applied to any municipality considering MAR for indirect potable reuse. According to the results of Chapter 4, the following conclusions can be drawn:

- Recharge water quality targets for MAR in Ontario can be defined based on Ontario and Health Canada drinking regulations and guidelines, Ontario Provincial Water Quality Objectives, and worldwide water reuse regulations/guidelines which specify requirements for MAR.
- Statistical analysis of WWTP effluent monitoring data is needed for the selection of predominant contaminants. The appropriate statistical method to deal with non-detects in monitoring data sets should be selected based on the purpose of study and data characteristics.
- Additional potential microbial and organic contaminants in wastewater effluents can be studied by selecting representatives from regulated contaminants in the defined parameter list based on their occurrences in wastewater effluents.
- Potential emerging organic chemicals can be studied by selecting representatives from the main groups of emerging contaminants based on their consumption volumes, bioaccumulation, ecological and health effects, and occurrences in wastewater effluents. Literature data can be useful in identifying contaminant concentrations for which wastewater effluent data at a specific location are not available.

6.1.3 Conclusions for Selection and Evaluation of Water Pre-treatment Technologies to Remove Critical Contaminants for MAR with Reclaimed Water

Water pre-treatment processes for MAR with reclaimed water are important for the removal of residual contaminants in wastewater effluents. Different types of water treatment technologies, including conventional wastewater treatment, conventional drinking water treatment, and advanced oxidation processes, can remove critical contaminants for MAR with reclaimed water. Based on the types of critical contaminants, different treatment alternatives can be proposed and evaluated based on the data in previous studies. According to the results of Chapter 5, the following conclusions can be drawn:

- Different types of treatment alternatives were proposed according to the categories of critical contaminants for MAR with reclaimed water, including microorganisms, nutrients, metals, salts, and trace organics.
- The removal efficiency of each critical contaminant by proposed treatment alternatives should be studied and evaluated in specific conditions based on the published studies.
- The target treatment efficiency and treatment efficiency credit were used as the tools for the selection of potential water treatment options to remove critical contaminants.
- Potential treatment trains can be proposed through the combination of different treatment units and treatment principles.
- The treatment train “Ultrafiltration + Reverse Osmosis + UV-based AOPs” was able to achieve the treatment goals defined in the study, and preliminary analysis showed that it was the most cost effective option. This recommendation should be verified based on further detailed experimental investigations, if a decision to proceed with MAR were to be made.

6.2 Recommendations

According to WWTP monitoring data and literature data, critical contaminants for MAR with reclaimed water were identified. However, the characteristics of the wastewater effluent used in this case study may be different from those of other WWTPs and those used the literature studies. To better understand the occurrence of these contaminants in wastewater effluents, monitoring for the identified critical contaminants in wastewater effluents should be conducted.

6.3 Future Work

Scenarios for the pre-treatment of MAR with reclaimed water were evaluated in this study. However, this assessment of potential treatment options was based on their performance under normal operating conditions. Some mechanical and operating failures of these treatments were not considered in the analysis. To reduce the risks which may be caused by these failures, a comprehensive risk assessment should be conducted.

Water treatment efficiency may vary depending on the characteristics of source water and operating conditions. To better evaluate the performance of this pre-treatment scenario, the recommended treatment train should be tested at both bench-scale and pilot-scale. In this way, treatment operating conditions can be optimized, which can be helpful for the implementation of full-scale treatment facilities in the future.

This study focused on water pre-treatment for MAR, but the actual recharge system was not looked at. In addition, the aquifer recharge system itself can serve as a natural barrier to remove the contaminants in water and reduce the pre-treatment requirements. Therefore, future work should also investigate the potential recharge sites, recharge methods, and recharge facility design and operation.

Appendix A

A Detailed Description of the Winsorized Mean Method

An example is used, where a contaminant concentration was measured with 24 data points. The detection limit for the method used was 1,450 mg/L, and 4 of the 24 values were below the detection limit.

Step 1: List the data in order from smallest to largest, including nondetects and label these points X_1, X_2, \dots, X_n . List the data above from smallest to largest.

<1450, <1450, <1450, <1450, 1575, 1710, 1760, 1760, 1770, 1780, 1780, 1780, 1780, 1790, 1790, 1790, 1800, 1800, 1800, 1820, 1840, 1850, 1860, 1900 mg/L.

Step 2: let n represent the number of data points, m represent the number above the detection limit and let $n-m$ represent the number below the detection limit.

$n=24, m=20, n-m=4$.

Step 3: Substitute $n-m$ nondetects with X_{m+1} and replace $n-m$ largest values with X_{n-m} .

The 4 nondetects are replaced with X_5 (1575) and 4 largest values are replaced with X_{20} (1820). The new data set is 1575, 1575, 1575, 1575, 1575, 1710, 1760, 1760, 1770, 1780, 1780, 1780, 1780, 1790, 1790, 1790, 1800, 1800, 1800, 1820, 1820, 1820, 1820, 1820 mg/L.

Step 3: Compute the mean of the revised data set.

The Winsorized mean is the average of the new data set. $\bar{X}=1744.375$

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