LOTT Clean Water Alliance

Reclaimed Water Infiltration Study
Phase 1 (Technical Data Review)

Technical Memorandum – "State of the Science"

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HDR

606 Columbia Street NW
Suite 200
Olympia, WA 98501
(360) 570-4400

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Exhibits

[Note: Exhibits refer to tables, charts, figures, etc. that have been extracted directly from the reference documents NRC 2012 or USEPA 2012. Embedded in these exhibits are the actual table/chart/figure number that is associated with the source document, so as to aid the reader in locating the pertinent portion of that primary source document for further review.]

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Contributing Authors

Peter Fox, Ph.D
Jeff Hansen, PE (HDR Engineering, Inc.)
John Koreny, RPG, PHG (HDR Engineering, Inc.)

Acronyms

ADI	Acceptable Daily Intake
AOP	Advanced Oxidation Process
BDOC	Biodegradable Organic Carbon
BNR	Biological Nutrient Removal
CAS	Conventional Activated Sludge
CECs	Contaminants of Emerging Concern
CPCs	Compounds of Potential Concern
DOC	Dissolved Organic Carbon
EDTA	Ethylenediaminetetracetic acid
EPA	United States Environmental Protection Agency
LOTT	LOTT Clean Water Alliance
MBR	Membrane Bioreactor
MCL	Maximum Contaminant Level
MF	Microfiltration
MOS	Margin of Safety
NDMA	N-nitrosodimethylamine
NF	Nanofiltration
NOM	Natural Organic Matter
NTA	Nitrilotri Acetic Acid
POC	Particulate Organic Carbon
PPCPs	Pharmaceuticals and Personal Care Products
QSAR	Quantitative Structure Activity Relationships
RBAL	Risk-Based Action Level
RfD	Reference Doses
RO	Reverse Osmosis
RWIS	Reclaimed Water Infiltration Study
SAT	Soil Aquifer Treatment
SWRCB	California State Water Resources Control Board
TDS	Total Dissolved Solids
TM	Technical Memorandum
TOC	Total Organic Carbon
TTCs	Thresholds of Toxicological Concern
UF	Ultrafiltration
UV	Ultraviolet

1.0 Introduction

1.1 Background

The LOTT Clean Water Alliance (LOTT) is a public, non-profit entity formed by its four government partners – the Cities of Lacey, Olympia, and Tumwater, and Thurston County. LOTT is responsible for providing wastewater treatment and management for the urban areas in northern Thurston County. While treatment currently occurs primarily at the Budd Inlet Treatment Plant, with treated effluent discharged to the marine waters of Budd Inlet, LOTT's long-range plan relies on the production and beneficial use of reclaimed water to meet northern Thurston County's growing demand for wastewater management. Reclaimed water can be used for a variety of non-drinking applications such as water features, toilet flushing, or irrigation. Reclaimed water not used for such purposes can be infiltrated to recharge groundwater, consistent with standards developed by the Washington State Departments of Ecology and Health. LOTT currently operates two reclaimed water plants and one groundwater recharge site, and has purchased properties to eventually expand the reclaimed water program.

Recently, questions and concerns about infiltration of reclaimed water have been raised. In particular, questions have focused on compounds of potential concern (CPCs), such as those originating from pharmaceuticals and personal care products. To address these questions, LOTT is undertaking a multi-year study to improve the scientific understanding of how infiltrated reclaimed water interacts with local groundwater, where these compounds exist in the environment, and what happens to them over time. Results of the Reclaimed Water Infiltration Study (RWIS), combined with extensive community dialogue, will help determine if adjustments to LOTT's long-range plan are needed.

1.2 Purpose and Organization of Technical Memorandum

The RWIS is being implemented in phases, with Phase 1 involving a variety of background activities that will inform the development of a detailed study scope of work, which will be prepared in Phase 2. One Phase 1 activity is a review of the current scientific understanding of the interactions between reclaimed water and groundwater, with a focus on CPCs. This technical memorandum provides a summary of this review, based upon a survey of existing literature on related scientific research. As such, this document will be referred to generally as the "State of the Science" technical memorandum.

The focus of this document is upon currently non-regulated CPCs and their interactions with groundwater, in the context of groundwater recharge of reclaimed water. However, to provide a broader context and describe the "state of the science" as it relates more comprehensively to reclaimed water and the future of this water resource, additional topics are covered. This technical memorandum is organized as follows:

- Section 2 – Major Classes of Contaminants Present in Wastewater, Treated Wastewater, and Reclaimed Water
- Section 3 – Contaminant Removal through Wastewater Treatment and Water Reclamation (In-Plant) Processes
- Section 4 – Contaminant Removal through Soil Aquifer Treatment
- Section 5 – Relative Risks Associated with Reclaimed Water
- Section 6 – Summary

- Section 7 – References

Sections 2, 3, and 5 rely heavily on information presented in a recently published book: "Water Reuse - Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater (NRC, 2012)". Published by the National Research Council, this document was authored by leading experts representing a broad spectrum of fields and disciplines that relate to reclaimed water, and provides a comprehensive compilation of the current scientific understanding of that resource. So as not to "reinvent the wheel", and for simplicity and brevity, key summary information is referenced and extracted directly from this compendium of relevant research. Pertinent summary tables and graphics from NRC 2012 have been inserted directly into this document as exhibits[1], with minimal narrative text. For more detail regarding the topics covered in these three sections, the reader is directed to NRC 2012.

A wider and more detailed literature review was conducted in the preparation of Section 4, as the topic of soil aquifer treatment efficacy is a primary focus of the RWIS. Therefore, more detail is presented in that section, as compared with the others, in order to provide a more robust understanding of this topic.

2.0 Major Classes of Contaminants Present in Wastewater, Treated Wastewater, and Reclaimed Water

Municipal wastewater collection systems receive wastes containing a wide range of biological, inorganic, and organic constituents. Compounds of potential concern in reclaimed water are variable and depend upon the nature of the raw wastewater coming into the treatment system. That being said, the major classes of contaminants typically considered in the context of wastewater management and reclaimed water production/use are organized as follows.

2.1 Pathogens

Pathogens represent that subset of microorganisms in wastewater that can cause infection in humans. These include enteric protozoa, viruses, and bacteria. In the United States, the most frequently documented waterborne pathogens are *Cryptosporidium* and *Giardia* (protozoa), and *Salmonella, Shigella,* and *Escherichia coli* (bacteria). Exhibit 2-1 provides a summary of the microorganisms that have been associated with waterborne disease outbreaks. Typical primary and secondary wastewater treatment processes attenuate microbial pathogens, but do not eliminate them. Additional physical or chemical processes are necessary to achieve the level of inactivation acceptable for most uses. This is described in more detail in Chapter 3.

[1]See note on Page ii regarding exhibits.

Exhibit 2-1. Summary of Pathogens
(From: NRC 2012)

TABLE 3-1 Microbial Agents of Known Hazard Via Water Exposures

Agent	Associated Illnesses
Viruses	
• Noroviruses	Gastroenteritis
• Adenoviruses	Conjunctivitis, gastroenteritis, respiratory disease, pharyngoconjunctival fever
• Coxsackieviruses	Meningitis, pharyngitis, conjunctivitis, encephalitis
• Echoviruses	Gastroenteritis, encephalitis, meningitis
• Hepatitis A virus	Hepatitis
• Astroviruses	Gastroenteritis
Bacteria	
• *E. coli* O157	Hemorrhagic diarrhea
• *Campylobacter jejuni*	Campylobacteriosis
• *Salmonella*	Salmonellosis
• *Shigella*	Shigellosis
• *Vibrio*	Gastroenteritis, wound infection
• *Legionella*	Legionellosis
Protozoa	
• *Cryptosporidium*	Cryptosporidiosis
• *Giardia*	Giardiasis
• *Microsporidia*	Microsporidiosis

NOTE: These agents are known to be present in treated wastewaters or surface water and therefore are considered to be potentially present in waters used for the production of reclaimed water.
SOURCE : Asano et al. (2007).

2.2 Inorganic Chemicals

A variety of inorganic chemicals are present in wastewater including nutrients, metals, and salts. Aggregate measures such as total dissolved solids (TDS) and conductivity are typically used to characterize the inorganic contents of wastewater.

With regard to nutrients, the primary concern associated with human health is related to elevated nitrate levels in drinking water. Potential environmental impacts include ammonia toxicity to fish and eutrophication due to excess algal growth which may be promoted by phosphorus and nitrogen loadings to water bodies.

Toxic metals, such as lead, mercury, and arsenic in secondary effluents are typically below established human health exposure limits.

The concentration of dissolved salts in reclaimed water is typically higher than that in groundwater or potable water used for irrigation purposes. Generally the levels observed in reclaimed water do not exceed thresholds of concern to human health. However, elevated levels of some salts can lead to corrosion in water infrastructure, while excess salinity can be detrimental to plant growth.

2.3 Organic Chemicals and Compounds of Potential Concern

Wastewater contains a substantial amount of organic material. This is characterized according to the following parameters:

- Total Organic Carbon (TOC) – Measure of all organic matter in a water sample.
- Dissolved Organic Carbon (DOC) – Portion of TOC that passes a 0.45 mm pore-size filter.
- Particulate Organic Carbon (POC) – Portion of TOC that does not pass the filter.

The vast majority of DOC in treated wastewater and reclaimed water is comprised of natural organic matter and soluble microbial products. A very small fraction of DOC is represented by a variety of individual organic chemicals at small concentrations. These are chemicals that originate from industrial and domestic products and activities, are excreted by humans, or are chemical by-products formed during wastewater or water treatment processes. Exhibit 2-2 provides a summary of the various types of these trace organic chemicals.

Exhibit 2-2. Summary of CPC Categories
(From: NRC 2012)

TABLE 3-3 Categories of Trace Organic Contaminants (Natural and Synthetic) Potentially Detectable in Reclaimed Waters

Category	Examples
Industrial Chemicals	1,4-Dioxane, perflurooctanoic acid, methyl tertiary butyl ether, tetrachloroethane
Pesticides	Atrazine, lindane, diuron, fipronil
Natural chemicals	Hormones (17β-estradiol), phytoestrogens, geosmin, 2-methylisoborneol
Pharmaceuticals and metabolites	Antibacterials (sulfamethoxazole), analgesics (acetominophen, ibuprofen), beta-blockers (atenolol), antiepileptics (phenytoin, carbamazepine), antibiotics (azithromycin), oral contraceptives (ethinyl estradiol)
Personal care products	Triclosan, sunscreen ingredients, fragrances, pigments
Household chemicals and food additives	Sucralose, bisphenol A (BPA), dibutyl phthalate, alkylphenol polyethoxylates, flame retardants (perfluorooctanoic acid, perfluorooctane sulfonate)
Transformation products	*N*-Nitrosodimethylamine (NDMA), bromoform, chloroform, trihalomethanes

These chemicals are referred to by many names. The most common ones include:

- Trace Organic Contaminants. This is the term used in NRC 2012.
- Compounds of Potential Concern (CPCs). This is the term that LOTT is currently using in the context of the RWIS, and which is therefore used most often throughout this TM.
- Contaminants of Emerging Concern (CECs). The United States Environmental Protection Agency (EPA) has defined CECs as "pollutants not currently included in routine monitoring programs" that "may be candidates for future regulation depending on their ecotoxicity, potential health effects, public perception, and frequency of occurrence in environmental media" (NRC 2012).
- Microconstituents.
- Micropollutants.
- Pharmaceuticals and Personal Care Products (PPCPs). This term refers to only two representative classes of CPCs; however, it is often used to represent the entirety of all CPC classes. In addition, PPCPs have received a great deal of attention recently, particularly in the media.

CPCs are typically present in treated wastewater and reclaimed water at microgram per liter (mg/L, or parts per billion) and lower levels. Most of them are measured at the nanogram per liter level (ng/L, or parts per trillion). With modern instrumentation, these low concentrations of CPCs are often detected in treated wastewater and reclaimed water, as well as drinking water.

Many CPCs have multiple pathways into the environment, with the discharge of treated wastewater or the final use of reclaimed water being only one such pathway. For example, some naturally occurring chemicals, such as estrogen hormones, are produced and excreted by animals and thus can enter the environment via any pathway that connects animal waste to a waterbody.

Most organic chemicals are not fully removed or destroyed during wastewater treatment processes. Although some chemicals are attenuated through disinfection and oxidation, the total concentration of DOC typically remains unchanged. This indicates that some chemicals are being transformed. A currently high-profile example of this is *N*-Nitrosodimethylamine (NDMA), a disinfection byproduct closely linked to chloramination and long considered a carcinogen. NDMA is a focus of attention due to its persistence through advanced treatment processes, including reverse osmosis.

3.0 Contaminant Removal through Wastewater Treatment and Water Reclamation (In Plant) Processes

There are numerous combinations of processes used in wastewater treatment and reclamation to remove the contaminants described in Section 2 to levels that are acceptable (per established regulatory standards) for the various uses or disposition of the resultant product water. Exhibit 3-1 summarizes the most commonly employed processes. The following sections provide a brief description of each category of treatment process.

Exhibit 3-1. Summary of Water Reclamation Treatment Processes
(From: NRC 2012)

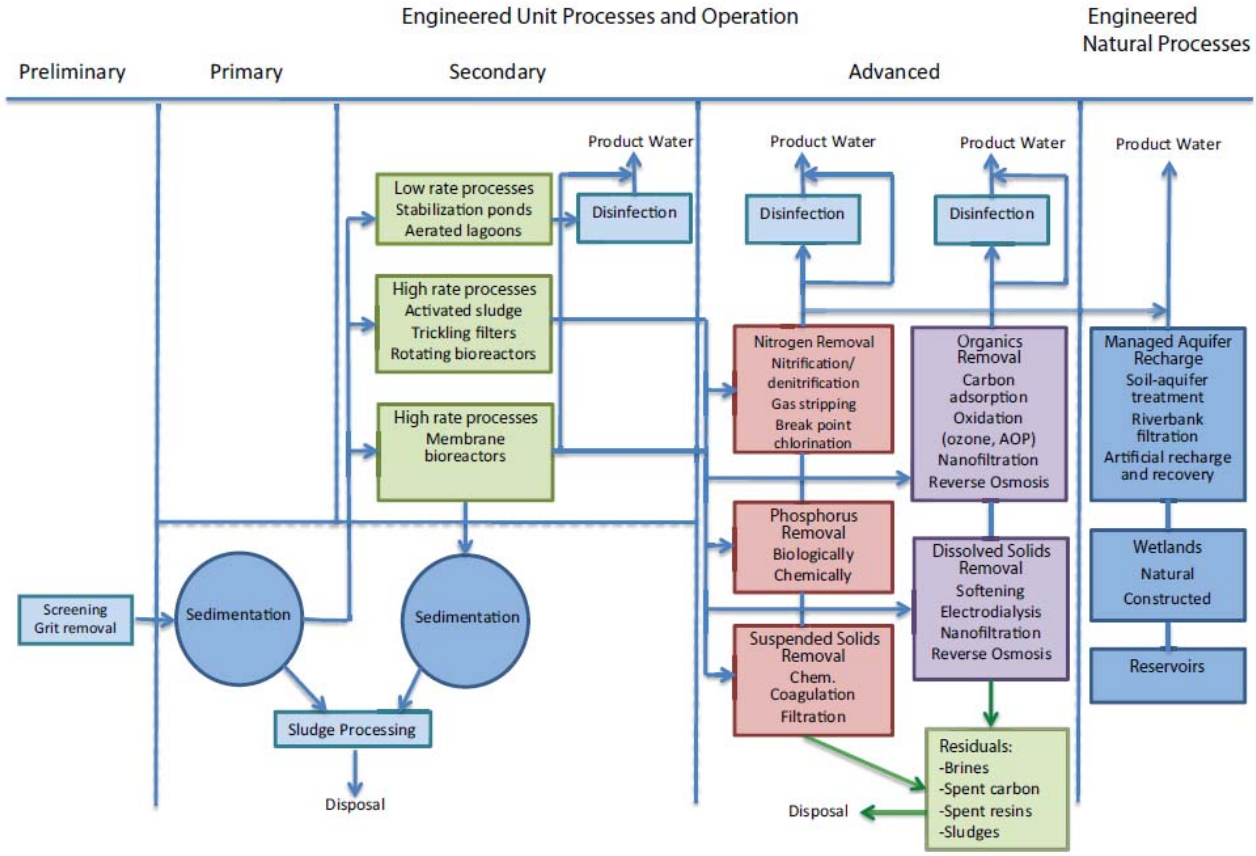

FIGURE 4-1 Treatment processes commonly used in water reclamation. Note that some or all of the numerous steps represented under advanced processes may be employed, depending on the end-product water quality desired and whether engineered natural processes are also used. All possible combinations are not displayed here.

3.1 Preliminary, Primary, and Secondary Treatment

Throughout this document, the term "treated wastewater effluent" generally refers to wastewater that has undergone at a minimum preliminary, primary, and secondary treatment. Preliminary treatment is comprised of screening large solid material and removing grit. Primary treatment removes material that either readily settles or floats. Only 1.3 percent of wastewater treatment plants in the US discharge effluent that receives only preliminary and primary treatment (NRC 2012).

Secondary treatment removes suspended solids, dissolved organic matter (measured as biochemical oxygen demand), and nutrients (to an extent). Biological and physical separation processes are employed in secondary treatment. An example is a conventional activated sludge (CAS) process followed by solids separation through settling or membrane filtration. Increasingly, membrane bioreactors (MBRs) are being utilized as they often require minimal or no primary treatment and secondary sedimentation.

The treatment processes employed in secondary treatment rely mainly upon sorption and biodegradation for the removal of the contaminants mentioned above. These are the same primary removal mechanisms that are active in soil aquifer treatment; thus, more detail is provided on these in Section 4.

3.2 Disinfection

Disinfection processes are designed to destroy pathogens. Typical disinfection processes utilize chlorine (gaseous or liquid forms), ultraviolet (UV) radiation, or ozone. While the use of chlorine is currently the most common form of disinfection in wastewater treatment systems, the use of UV has been increasing.

The effectiveness of the various disinfectants in pathogen reduction is a function of the amount of disinfecting agent introduced to the water, the contact time provided, and other water quality parameters that may compete for the disinfectant or otherwise alter its effectiveness against pathogens. The most common measure of effectiveness is *Ct*. This is the product of residual disinfectant concentration (or power intensity, in the case of UV) and the contact time. Exhibit 3-2 depicts the general relationship between *Ct* and pathogen reduction (inactivation) for various disinfectants.

In most disinfection systems, except UV, bacteria are more readily disinfected than viruses, which are more easily disinfected than protozoa. In UV systems, protozoa are usually more easily disinfected than viruses.

Exhibit 3-2. Summary of Disinfection Requirements by Process Type
(From: NRC 2012)

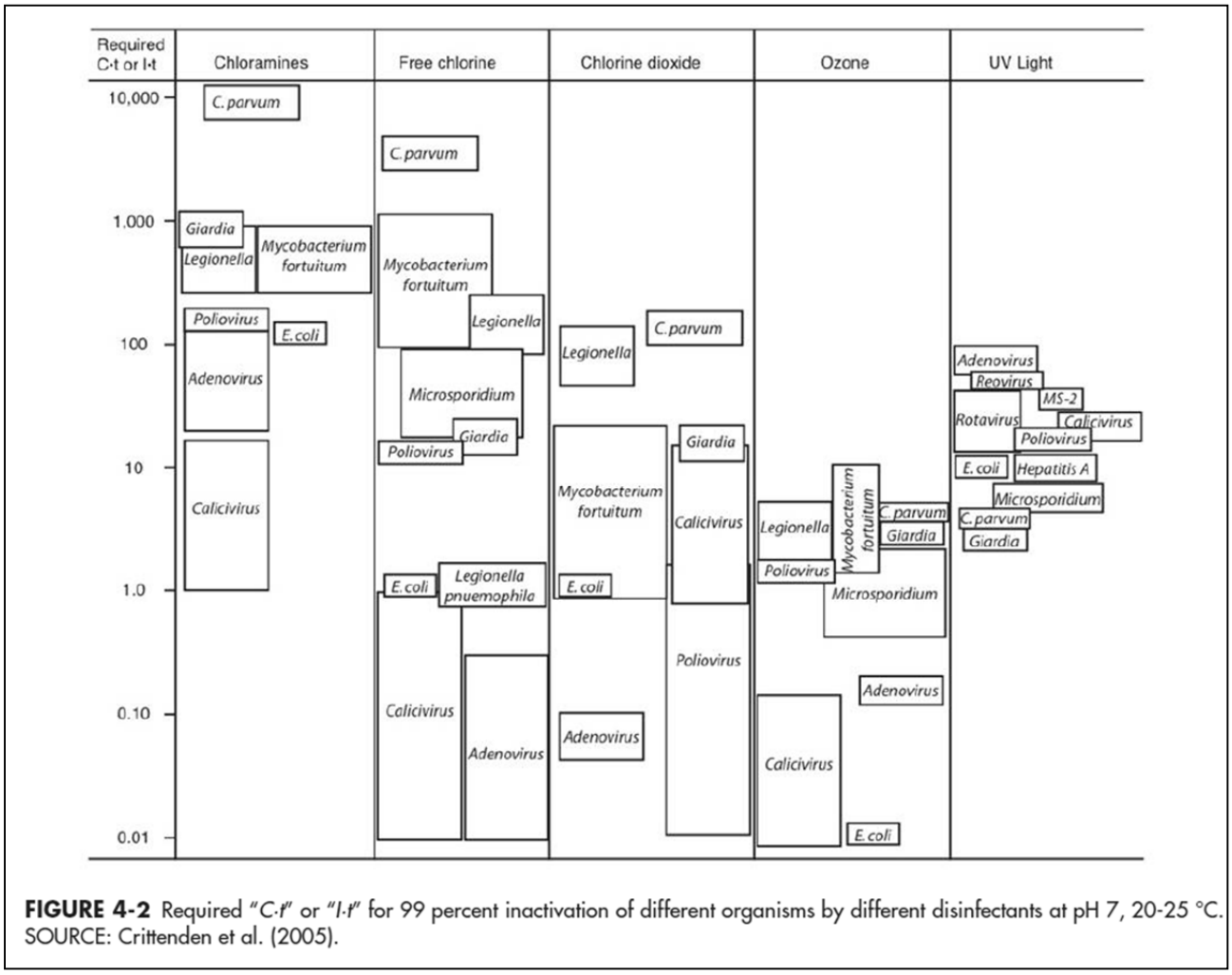

FIGURE 4-2 Required "C·t" or "I·t" for 99 percent inactivation of different organisms by different disinfectants at pH 7, 20-25 °C.
SOURCE: Crittenden et al. (2005).

3.3 Advanced Treatment

Advanced treatment is a broad term referring to many additional treatment processes that target the removal of nutrients and organic compounds, reduction of TDS, or provision of additional barriers to pathogens. Often, multiple advanced treatment processes are combined to meet multiple water quality objectives. NRC 2012 provides a detailed description of the many processes that are currently employed. Two general categories of advanced treatment processes that are often used to remove CPCs, as well as other contaminants, are described briefly below. This is not an exhaustive list of treatment processes, but those commonly used.

3.3.1 Membrane Filtration

Various types of membrane filtration are used to remove organic matter and pathogens. Microfiltration (MF) and ultrafiltration (UF) membranes can be installed in either pressurized or submerged configurations. These systems are quite effective at removing microorganisms. MF

removal of bacteria and protozoa are on the order of 90 to 99.999 percent (1 to 5 log removal), while virus removal ranges from 0 to 99 percent (0 to 2 log removal).

In situations where additional removal of dissolved solids and CPCs is required, nanofiltration (NF) or reverse osmosis (RO) may be used. These are pressure-driven membrane processes that separate dissolved constituents into a permeate (clean) stream and a concentrate stream. These processes typically result in water recoveries of 70-85 percent; thus, there can be significant volumes of brine concentrate waste that must be managed. These systems are very effective at removing trace organic matter. However, there are some constituents that selectively pass through these membranes, such as low-molecular-weight organic acids and neutrals (e.g., NDMA) and some disinfection byproducts (e.g., chloroform).

3.3.2 Advanced Oxidation Processes

Advanced oxidation processes (AOPs) are combinations of UV plus hydrogen peroxide, ozone plus hydrogen peroxide, and UV plus ozone that are specifically designed to increase the formation of powerful hydroxyl radicals (OH-) to oxidize resistant compounds, including CPCs. For example, some wastewater treatment systems employing MBR followed by ozone have demonstrated estrogenicity reduction greater than 99.9% (Cleary, 2011). Substances that are difficult to biodegrade may be oxidized by AOPs, and the oxidized byproducts may then be more amenable to biodegradation.

It is important to note that although these systems may be effective at oxidizing certain constituents, they typically are not capable of mineralizing organic material. Thus, through such processes constituents are often transformed, with the total DOC concentration minimally reduced. Some of these byproducts have yet to be fully characterized.

3.4 Summary of Treatment Process Removal Efficiencies

The treatment processes summarized above have ranges of effectiveness regarding the removal of the various contaminants discussed in Section 2. Exhibit 3-3 provides a summary of typical water quality after various types of secondary treatment. Exhibit 3-4 is a more comprehensive summary of CPC removal efficiencies associated with the range of treatment processes. This summary compares various engineered systems (physical, chemical, and biological) with natural systems, including soil aquifer treatment (which is discussed in greater detail in Section 4).

Conventional secondary wastewater treatment (i.e., activated sludge) has a percent removal of more than 90% for some CPCs, but less than 10% for others. Advanced treatment in the form of reverse osmosis has a percent removal of more than 95% for most CPCs, with one exception being NDMA (having a removal rate of 25-50%). Soil aquifer treatment has been observed to have a percent removal of more than 90% for most CPCs, with specific compounds persisting for long times in SAT systems, such as carbamazepine (an anti-epileptic drug).

Exhibit 3-3. Summary of Reclaimed Water Quality after Treatment

(From: NRC 2012)

TABLE 3-2 Reported Ranges of Reclaimed Water Quality for Key Water Quality Parameters After Different Degrees of Treatment

			Range of Effluent Quality After Indicated Treatment				
Constituent	Units	Untreated Wastewater	Conventional Activated Sludge (CAS)	CAS with Filtration	CAS with Biological Nutrient Removal (BNR)	CAS with BNR and Filtration	Membrane Bioreactor (MBR)
Total suspended solids (TSS)	mg/L	120–400	5–25	2–8	5–20	1–4	<2
Total organic carbon (TOC)	mg-C/L	80–260	10–40	8–30	8–20	1–5	0.5–5
Total nitrogen	mg-N/L	20–70	15–35	15–35	3–8	2–5	<10[a]
Total phosphorus	mg-P/L	4–12	4–10	4–8	1–2	≤2	<0.3[b]–5
Turbidity	NTU	—	2–15	0.5–4	2–8	0.3–2	≤1
Volatile organic compounds (VOCs)	µg/L	<100->400	10–40	10–40	10–20	10–20	10–20
Trace constituents	µg/L	10–50	4–40	5–30	5–30	5–30	0.5–20
Total coliforms	No./100 mL	10^6–10^9	10^4–10^5	10^3–10^5	10^4–10^5	10^4–10^5	<100
Protozoan cysts and oocysts	No./100 mL	10–10^4	10–10^2	0–10	0–10	0–1	0–1
Viruses	PFU/100 mL	10–10^4	10–10^3	10–10^3	10^1–10^3	10–10^3	1–10^3

NOTE: None of the treatments in the table include disinfection.

[a]With anoxic zone.

[b]With coagulant.

Exhibit 3-4. Summary of CPC Removal Efficiencies of Various Treatment Processes

(From: USEPA 2012)

Table 6-5 Indicative percent removals of organic chemicals during various stages of wastewater treatment

Treatment	Percent Removal										
			Pharmaceuticals					Hormones			
	B(a)p	Antibiotics[1]	DZP	CBZ	DCF	IBP	PCT	Steroid[2]	Anabolic[3]	Fragrance	NDMA
Secondary (activated sludge)	nd	10–50	nd	–	10–50	>90	nd	>90	nd	50–90	–
Soil aquifer treatment	nd	nd	nd	25–50	>90	>90	>90	>90	nd	>90	>90
Aquifer storage	nd	50–90	10–50	–	50–90	50–90	Nd	>90	nd	–	–
Microfiltration	nd	<20	<20	<20	<20	<20	<20	<20	nd	<20	
Ultrafiltration/ powdered activated carbon (PAC)	nd	>90	>90	>90	>90	>90	nd	>90	nd	>90	>90
Nanofiltration	>80	50–80	50–80	50–80	50–80	50–80	50–80	50–80	50–80	50–80	
Reverse osmosis	>80	>95	>95	>95	>95	>95	>95	>95	>95	>95	25–50
PAC	>80	20–>80	50–80	50–80	20–50	<20	50–80	50–80	50–80	50–80	
Granular activated carbon		>90	>90	>90	>90	>90		>90		>90	>90
Ozonation	>80	>95	50–80	50–80	>95	50–80	>95	>95	>80	50–90	50–90
Advanced oxidation		50–80	50–80	>80	>80	>80	>80	>80	>80	50–80	>90
High-level ultraviolet		20–>80	<20	20–50	>80	20–50	>80	>80	20–50	nd	>90
Chlorination	>80	>80	20–50	–<20	>80	<20	>80	>80	<20	20–>80	–
Chloramination	50–80	<20	<20	<20	50–80	<20	>80	>80	<20	<20	

(Sources: Ternes and Joss, 2006; Snyder et al., 2010)

B(a)p = benz(a)pyrene; CBZ = carbamazepine, DBP = disinfection by-product; DCF = diclofenac; DZP = diazepam; IBP = ibuprofen; NDMA=N-nitrosodimethylamine; nd = no data; PAC = powdered activated carbon; PCT = paracetamol.

[1] erythromycin, sulfamethoxazole, triclosan, trimethoprim

[2] ethynylestradiol; estrone, estradiol and estriol

[3] progesterone, testosterone

4.0 Contaminant Removal through Soil Aquifer Treatment

This section summarizes the major operational, biological and chemical processes that govern and influence the contaminant removal efficiency of soil aquifer treatment (SAT) systems that involve recharging groundwater with reclaimed water. This section begins with a definition of SAT systems, followed by discussion of important operational conditions (wetting/drying cycles and redox [i.e., aerobic versus anoxic or anaerobic] conditions), descriptions of the primary contaminant removal mechanisms (sorption and biodegradation), definition of current predictive approaches to determining removal efficiencies, discussion of other factors (such as subsurface travel times, vadose/saturated zones, temperature, and dilution), identification of compounds that persist through SAT systems, and a summary of current and emerging research areas related to SAT.

4.1 Introduction to Soil Aquifer Treatment

SAT may be viewed as part of a multi-component system containing both above ground and below ground elements, as illustrated in Figure 4-1. The above ground components consist of the reclaimed water source and associated treatment processes prior to groundwater recharge, and the subsequent extraction of post-SAT water for use. When reclaimed water percolates from recharge basins into the vadose (unsaturated) zone and then into the saturated zones of the underlying aquifer, the water quality is improved by chemical and biological processes. These subsurface processes, which occur in and below engineered recharge basins, collectively comprise a SAT system. SAT aids in the reduction of pathogens, TOC, nitrogen species, and CPCs that may be present in reclaimed water, as described in Section 2. Biodegradation is responsible for the majority of removal during SAT and is a sustainable process that continues indefinitely. The process of sorption of contaminants on the outside of soil particles also removes contaminants from groundwater.

Figure 4-2 is a schematic illustration of recharge basins and subsurface paths to a down-gradient recovery or monitoring well. The system may be viewed as a biological filter where various strata in the aquifer act as biofilm attachment surfaces, with each strata potentially having different removal characteristics.

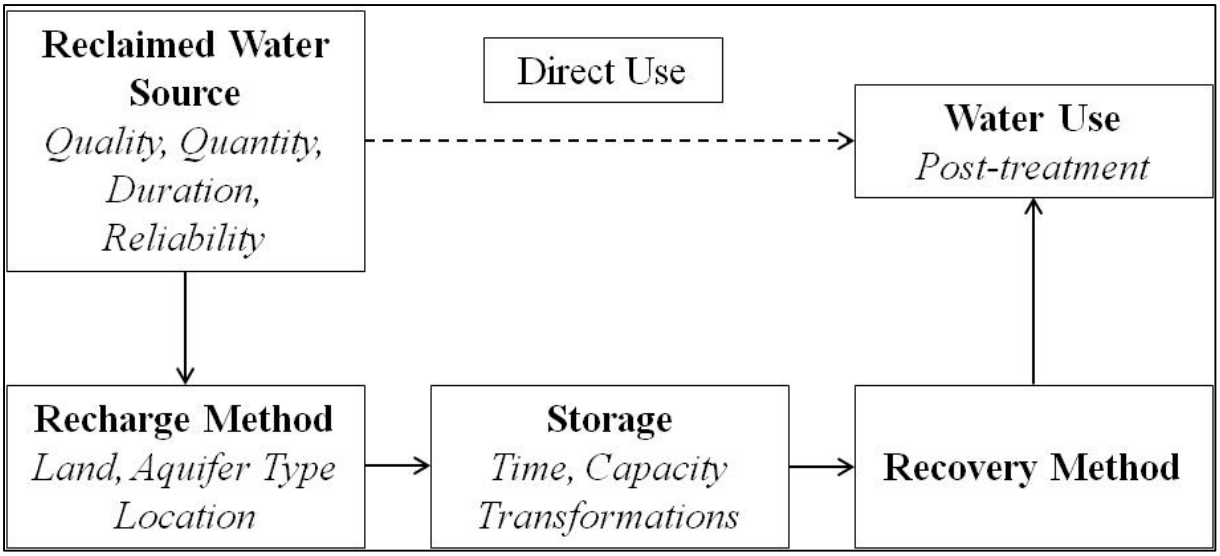

Figure 4-1. Components of a Soil Aquifer Treatment System

(Adapted from NRC, 2008) The bold words identify the five major components. The words in italics describe the major factors for design.

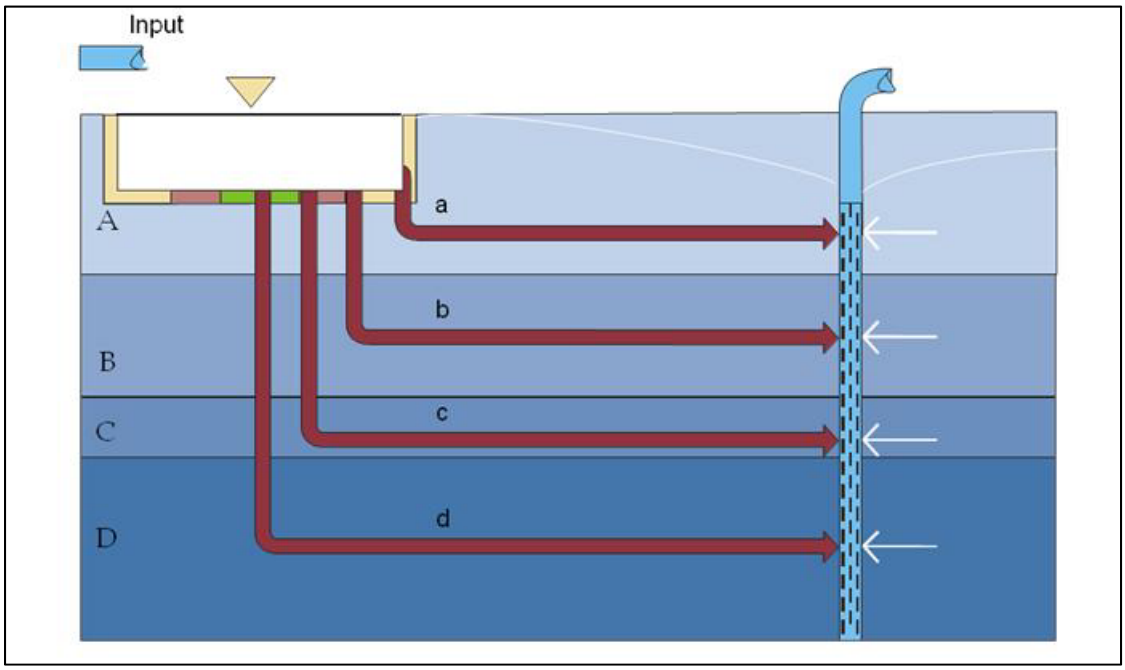

Figure 4-2. Schematic of Recharge Basin and Subsurface Flow Paths

Water infiltrating from a recharge basin (white rectangle in upper left) can take various paths (denoted by lowercase letters) to a recovery or monitoring well. These paths are well defined through various aquifer materials (denoted by uppercase letters) that support biofilm growth. The system is analogous to a biological filter.

A significant amount of research has been conducted to understand the performance of SAT systems in removing pathogens, disinfection by-product (DBP) precursors (i.e., TOC), nutrients, and CPCs (Drewes and Fox, 1999; Drewes and Fox, 2000; Leenheer et al., 2001; Fox et al., 2001, 2006; Drewes et al., 2003a,b; Drewes et al., 2006a,b; Hoppe-Jones et al., 2010; Rauch-

Williams et al., 2010). Many studies indicate that several factors affect performance of SAT systems and the quality of the water after SAT. Besides the reclaimed water quality being recharged, important factors influencing post-SAT water quality include recharge (or spreading) basin characteristics, subsurface conditions, the degree of blending with native groundwater, and operating conditions. Although SAT systems may have variable characteristics, their overall performance regarding the attenuation of CPCs has been consistent in monitored SAT systems and related systems such as bank filtration (i.e., the horizontal movement of water from a surface water body into groundwater, such as through a riverbank). This includes systems in North America, Europe, and Asia in a variety of climates and under a range of reclaimed water qualities.

4.2 Impact of Wetting/Drying Cycles

It is well known that the ideal operation of recharge basins requires the use of wetting and drying cycles to maintain infiltration rates. As water is applied to the basins, the upper layer of soil (i.e., the clogging layer) acts to filter out the suspended solids. In addition, biological activity increases the accumulation of organic matter in this upper layer of soil. These factors cause a reduction in soil permeability and infiltration rates over time. In areas with high solar radiation, algae growth can also be a major factor contributing to a reduction in infiltration rates. Infiltration rates will continue to decrease with time until the application of water is stopped.

As the recharge basin is drained and allowed to dry, the organic material on the surface of the soil will desiccate and infiltration rates will recover. Without a drying cycle the infiltration rates may become unacceptably low unless a submerged cleaning device is used to remove the clogging materials. Figures 4-3 and 4-4 are pictures of recharge basins during different phases of wetting and drying.

Figure 4-3 Recharge Basin Drying Cycle

(Source: AWWARF, 2001) Tucson Water Recharge Basin RB-008 at the beginning of a drying cycle. The water from the wetting cycle is almost completely drained.

Figure 4-4. Recharge Basin Wetting Cycle

(Source: AWWARF, 2001) City of Tucson, AZ, Aquifer Recharge Basin. The basins at the bottom of the picture are full during a wetting cycle. The basins in the distance are beginning a drying cycle.

The use of wetting/drying cycles also has an important affect on the microbial reactions in the subsurface. During wetting, the dissolved oxygen in the infiltrating water becomes exhausted from carbonaceous and nitrogenous oxygen demand. As the soil pores become saturated, anoxic conditions develop and persist since there is no opportunity to introduce oxygen to the saturated zone. However, drying allows air to be drawn back into the vadose zone and aerobic conditions to redevelop. If ammonia is adsorbed during a wetting cycle, the ammonia can be nitrified during a drying cycle resulting in a flush of nitrate during the initial portion of a wetting cycle. Changes occurring with ammonia and oxygen during a wetting and drying cycle are illustrated in Figure 4-5.

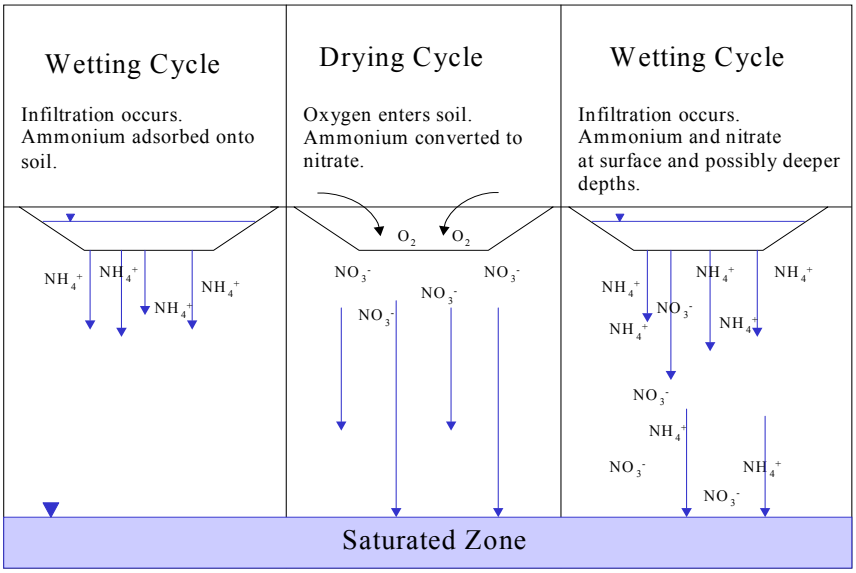

Figure 4-5. Changes in Nitrogen during Wetting and Drying Cycles

(Source: AWWARF, 2001) During wetting, ammonia is removed by sorption onto clay materials in the soil. During drying, oxygen is drawn into the soil and ammonia may be nitrified. During subsequent wetting cycles, nitrate may be flushed from the soil.

4.3 Impact of Redox Conditions

Treatment processes employed in the production of reclaimed water (i.e., at a treatment plant) determine the quality of the water (including the level of total oxygen demand) applied to recharge basins. This has a significant role in dictating the redox conditions (i.e., aerobic versus anoxic or anaerobic) in a SAT system, which in turn impacts the biological activity and associated removal efficiencies.

This is most notably observed near the soil/water interface where high biological activity is present. This level of activity occurs because biodegradable matter and oxygen are both present at their highest concentrations at this location in the SAT system. The level and type of reclaimed water treatment directly impacts the concentrations of biodegradable matter that are applied to a recharge basin. Both organic carbon and ammonia may be biologically oxidized and they are the water quality parameters controlling the amount of oxygen demand in applied waters.

For example, the concentration of dissolved organic carbon in reclaimed water typically ranges from 4 to 20 mg/L, and the corresponding carbonaceous biological oxygen demands may range from less than 2 mg/L to greater than 20 mg/L. Ammonia-N concentrations may range from less than 1 mg/L to greater than 20 mg/L, and the corresponding nitrogenous oxygen demands may range from less than 1 mg/L to greater than 80 mg/L. Reclaimed water treated by conventional biological treatment can contain greater than 20 mg NH_3-N/L and have a total oxygen demand in excess of 100 mg/L. By contrast, reclaimed water treated by advanced biological treatment including nitrogen removal can contain 0 mg NH_3-N/L and 8 mg DOC/L with a total oxygen demand less than 5 mg/L. As such, reclaimed water treatment that removes nitrogen can greatly reduce the total oxygen demand of applied water. This allows the oxygen level to remain suitable to maintain aerobic conditions at the soil/water interface and support biological growth. The majority of oxygen demand exerted during wetting is from the oxidation of organic carbon while ammonia is mostly removed by adsorption.

The impact of reclaimed water qualities upon redox conditions can be seen in the following examples. At the San Gabriel Spreading Grounds (part of the Montebello Forebay) in Los Angeles County, partially nitrified/denitrified waters are applied along with stormwater and other sources of water (AWWARF, 2001). The low total oxygen demand in waters applied result in aerobic conditions in both the vadose zone and the saturated zone since all the dissolved oxygen in the applied waters is not utilized. By contrast, at the Tucson Sweetwater Underground Storage and Recovery Facility, high total oxygen demand maintains anoxic conditions throughout the majority of the wetting/drying cycle. Aerobic conditions only develop in the top 0-5 feet (0-1.5 m) of the vadose zone at the end of drying cycles. Dissolved oxygen is rapidly removed during wetting and pore gas oxygen is used for nitrification during drying. The large amount of adsorbed ammonia prevents pore gas oxygen concentrations from increasing before the next wetting cycle. These two examples represent the extremes for how reclaimed water treatment "upstream" of recharge basins can impact redox conditions. At the Mesa Northwest Water Reclamation Plant where advanced biological treatment including nitrification/denitrification produces high quality reclaimed water, anoxic conditions develop at a depth of 10 feet (3 m) and the plume of reclaimed water in the saturated zone is anoxic. The total oxygen demand from 1-2 mg/l of ammonia and 5-8 mg/l of TOC was still sufficient to remove the oxygen and the shallow vadose zone limits aeration during drying cycles.

Although the majority of oxygen demand is removed in the upper vadose zone during SAT, the total oxygen demand of the applied water influences the redox conditions in the saturated zone.

If dissolved oxygen is removed during percolation through the vadose zone, anoxic conditions are likely to develop in the saturated zone since mechanisms for oxygen transport to the saturated zone are insignificant. Many bank filtration systems in Europe result in anoxic saturated zones since there is no vadose zone and wetting/drying cycles cannot be applied.

Although redox conditions can vary greatly as noted above, it is important to note that redox conditions do not have a significant effect on the removal of DOC. The removal of DOC during SAT under both aerobic conditions and anoxic conditions is on a time scale of several weeks. Since most SAT systems have operational time scales of many months or years prior to water being extracted for use, there is no discernable impact of redox conditions on DOC removal in post-SAT water. Figure 4-6 provides an example where the removal of DOC under aerobic conditions and anoxic conditions was compared under both laboratory and field conditions. The initial rate of removal under aerobic conditions is faster, but after 20 days the concentration of DOC is the same under both anoxic and aerobic conditions.

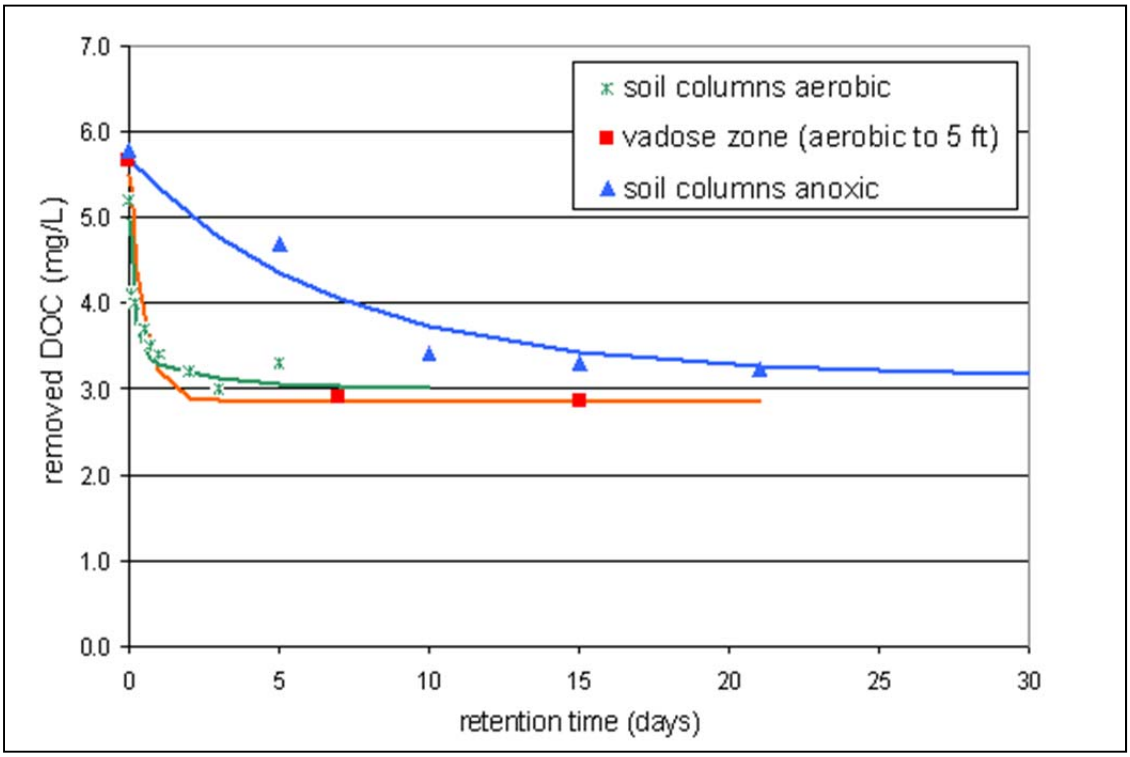

Figure 4-6. Impact of Redox Conditions on DOC Removal

(Source: Naranaswamy, 2001) Dissolved Organic Carbon (DOC) removal under both aerobic and anoxic conditions. After 20 days, the DOC concentrations are similar under both redox conditions.

Although varying redox conditions are not significant with regard to DOC removal, they are a factor that can result in differences in the removal efficiencies of various CPCs during SAT. For example, sulfamethoxazole and carbendazim were not degraded under aerobic conditions while they were much more rapidly degraded in anoxic environments (Gunther and Jekel, 2005). The opposite effect of redox conditions on the biodegradation of other compounds, such as phenazone, has also been reported under aerobic conditions while attenuation was limited under anoxic conditions (Stuyfzand et al, 2007).

Alternating the redox conditions between anoxic and aerobic can aid in the biodegradation of some compounds. This is particularly true for highly chlorinated compounds which cannot be initially degraded under aerobic conditions. Dechlorination under anaerobic or anoxic conditions can produce a partially dechlorinated compound that can then be degraded further under aerobic conditions. Highly chlorinated compounds are typically not found in reclaimed water as most highly chlorinated compounds have very low solubility in water. Varying redox conditions typically only occurs in the vadose zone where the degradation of hydrophobic compounds that adsorb to the soil may benefit from varying redox conditions.

The majority of compounds biodegrade under both aerobic and anoxic conditions (Rittmann, 2001). Biological growth rates under anoxic conditions are almost as fast as aerobic conditions. Since many soil bacteria are facultative (i.e., they can metabolize carbon and nutrients under either aerobic or anerobic conditions), more than 80% of the enzymes associated with biotransformations are similar under both aerobic and anoxic conditions. Redox conditions can have an effect, but the effect is primarily limited to the compounds described above.

4.4 Sorption

Sorption refers to the removal of a compound from the water phase onto the solid phase. This serves as one of the contaminant removal mechanisms that occur during SAT. The ability of a compound to adsorb to aquifer materials is a function of the compound's hydrophobicity (i.e., the extent to which a compound dissolves in water). The hydrophobicity of a compound is usually quantified by its octanol-water partition coefficient ($\log K_{ow}$). Compounds with high $\log K_{ow}$ values may be strongly sorbed.

The sorption of compounds to soils is also considered to be a function of the soil organic carbon content. Over time, the fraction of organic carbon (f_{oc}) has been shown to decrease in SAT vadose zone soils as compared to non-SAT soils. This decrease is attributed to the infiltration of water and the increased microbial activity (Aboshanp and Fox, 2005). Studies have demonstrated that even strongly adsorbed compounds do not accumulate on SAT vadose zone soils (Quanrud et al., 2008). This is due to the subsequent effect of biodegradation. One exception is the presence of brominated flame retardants such as polybrominated diphenyl ethers. These compounds are strongly adsorbed and resist biodegradation and therefore may accumulate in SAT vadose zone soils. These compounds are also present at higher levels in biosolids and after years of application they have not transported a significant distance into the vadose zone.

The large capacity for sorption of hydrophobic compounds in SAT systems could provide removal for centuries even if the compounds are not transformed. After twenty years of operation in Tucson, the polybrominated diphenyl ethers are present only in the top foot of soil, as their concentrations in reclaimed water are low and they are very strongly adsorbed.

4.5 Biodegradation

Biodegradation is the major sustainable removal mechanism for organic compounds and CPCs during SAT. Bacteria metabolize carbon under both aerobic and anaerobic conditions. It is important to understand the nature of organic carbon in reclaimed water since the biodegradation of CPCs is related to the biodegradation of organic carbon.

TOC has long been used as an indicator for the removal of CPCs in California. However, the concentration and nature of TOC varies in reclaimed water depending on the source water and level of treatment. Therefore, TOC may not be a good absolute indicator of SAT efficiency at removing CPCs. Recently, it has been proposed that Biodegradable Organic Carbon (BDOC) could be a better indicator of the extent to which CPCs can be removed (CDPH, 2012). The bulk of TOC in tertiary treated effluents is composed of easily biodegradable materials and less-easily biodegradable refractory organic carbon. The method and efficiency of reclaimed water treatment influences the level of easily biodegradable organic carbon. Refractory dissolved organic carbon in reclaimed water is usually composed of residual natural organic matter (NOM), largely humic acids from drinking water, some soluble microbial products, and some anthropogenic and natural trace organic chemicals (including some CPCs). The NOM from drinking water persists during reclaimed water treatment, and therefore, the levels appear to be independent of conventional biological nutrient removal (BNR) processes but dependent upon the type of source water used for drinking water supply in the service area (Drewes and Fox, 2000). For tertiary effluent at nitrifying/denitrifying water reclamation facilities, the TOC level usually varies between 5 and 10 mg/L (Fox et al., 2006; Laws et al., 2011). CPCs represent a very small fraction of the organic carbon pool as they are measured at ng/l concentrations, which is six orders of magnitude lower than the bulk TOC measurement in mg/l.

The correlation between the TOC content of post-SAT water and the TOC in drinking water supplies provides evidence that the absolute TOC concentration in recharged water is independent of the degree of reclaimed water treatment (Drewes and Fox, 2000). SAT was studied using reclaimed water from seven different reclaimed water facilities located in three different states. Reclaimed water treatment processes ranged from trickling filters to advanced biological treatment. After treatment by Short Term SAT (defined by a travel time of 20 days), the post-SAT water DOC was independent of the initial DOC concentration (Figure 4-7). The post-SAT concentration was correlated with the drinking water source DOC concentration, clearly demonstrating the organic matter in drinking water is a major component of DOC in reclaimed water (Figure 4-8).

SAT can reduce DOC concentrations below drinking water DOC concentrations if sufficient travel time is present (Naraswamy et al., 2001). A comparison of results from SAT studies in Europe and the United States inspired the research to prove that absolute TOC concentrations were independent of reclaimed water treatment. Studies in Berlin, Germany demonstrated that SAT could effectively transform and reduce Dissolved Organic Carbon (DOC) to 5-6 mg/L which was similar to the native groundwater used as a drinking water supply (Fox et al., 2006). Ozonation was capable of decreasing the DOC concentration after SAT. The ozonation was effective since the recalcitrant TOC concentration in the drinking water source was high. Similar studies on SAT conducted in Tucson, Arizona also showed that DOC could be transformed effectively. In these studies the initial TOC concentration in the reclaimed water could be relatively high (15 mg/L), but the post-SAT concentration was 1-2 mg/L. Ozonation could increase the kinetics of DOC transformations but there was no effect on the post-SAT concentration. The drinking water source in Tucson is a pristine groundwater with DOC concentrations less than 1 mg/L and thus the reclaimed water did not contain much recalcitrant DOC of drinking water origin.

While SAT can provide the same level of treatment in terms of protecting public health in both Germany and Arizona, the use of an absolute TOC concentration would greatly limit groundwater recharge in Germany while the TOC concentration requirement would easily be met in Arizona. The use of BDOC as a performance measure, however, could be applied equally and uniformly in both locations.

The removal of DOC is sustained by biological removal mechanisms and there is significant evidence that DOC removal may continue indefinitely. At the Tucson Sweetwater Underground Storage and Recovery Facility, the profile of DOC carbon removal with depth has been monitored for over 20 years. The profile for DOC removal with depth has remained similar over this time period, during which millions of gallons of water have been applied to the recharge basins. Analysis of soil samples from SAT sites has also been done to characterize changes in the organic carbon content and other soil characteristics. At a depth below six inches, there is no evidence for organic carbon accumulation. In fact, the organic carbon content decreases as compared to adjacent soils with no exposure to reclaimed water. The steady infiltration of water stimulates biological activity and actually reduces the total carbon in the soil column. In addition, some bank filtration systems in Europe have been in operation over 100 years and continue to remove DOC effectively.

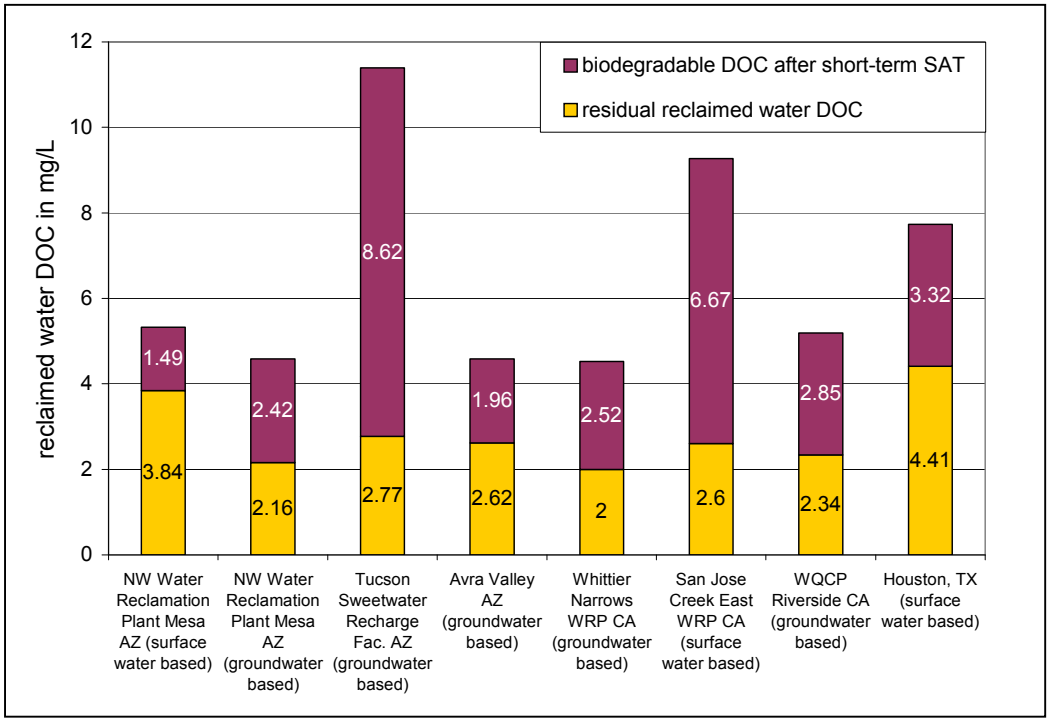

Figure 4-7. Short-term SAT studies with different reclaimed waters

(Source: Drewes and Fox, 2000) The DOC concentration after SAT was independent of the initial DOC concentration in the reclaimed waters. The drinking water sources for each facility are in parentheses. Mesa, AZ uses surface water most of the year and switches to groundwater during canal maintenance in the winter. The residual DOC concentration decreases by 44% when groundwater is the drinking water source.

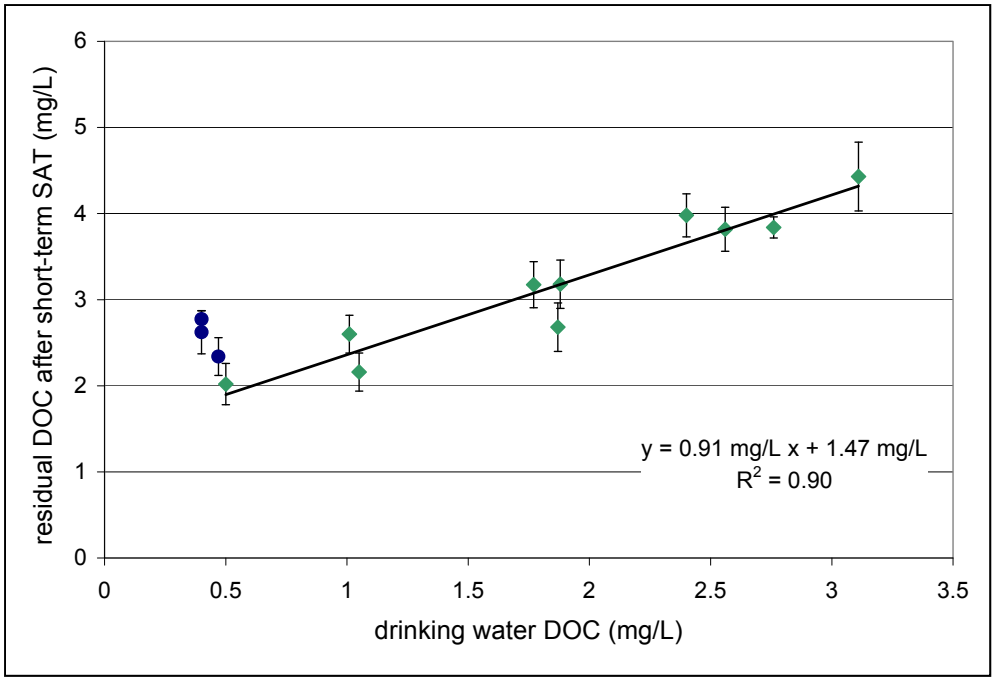

Figure 4-8. Relationship of Drinking Water DOC to Post-SAT DOC

(Source: Drewes and Fox, 2000) The DOC concentration after SAT was dependent on the DOC concentration in the drinking water DOC.

4.5.1 Effect of Sorption on Biodegradation

There are two primary mechanisms by which sorption may enhance the biotransformation of CPCs during SAT. Microbial communities in SAT systems are attached to aquifer materials. Sorption may enhance removal by ensuring that the compounds are adjacent to the microorganisms. Even if the compounds are adsorbed in pores too small for microbes, as the compound desorbs, the compound will have an increased chance of contacting a microbe. Therefore biodegradation is enhanced by the increased probability that the compound will contact a microbe.

The second mechanism is the effect of sorption on increasing the time required for a compound to travel the distance from a recharge site to recovery well. The effect of sorption may be quantified by a retardation factor and this may be estimated by the K_{ow} or the compound combined with the K_{oc} of the aquifer materials. The travel time of a CPC might be predicted to be 10 times the travel time of the infiltrating water during SAT. Under such a scenario, the compound will have a much greater time for biodegradation to occur.

4.5.2 Co-Metabolism

Both field monitoring efforts and controlled laboratory studies have demonstrated that SAT systems can effectively remove a wide range of CPCs (Amy and Drewes, 2007; Drewes et al., 2008; Laws et al., 2011) including those with demonstrated health relevance, such as NDMA (Drewes et al., 2006b). However, the metabolism of CPCs occurs as part of the microbial metabolism of BDOC. The transformation of organic CPCs clearly depends on the presence of BDOC since the concentrations of CPCs are very low and may not support growth by themselves (Rausch-Williams et al, 2010, Nalinakumari et al, 2010). CPC attenuation during SAT is mainly attributed to biologically-driven processes in which the available BDOC supports

the growth and metabolism of microorganisms. If a compound cannot directly support growth but it is metabolized, the transformation can be referred to as co-metabolism.

An example where co-metabolism is critical to transformations during SAT is the attenuation of NDMA, as depicted in Figure 4-9. The Orange County Water District and the Scottsdale Water Campus both produce reclaimed water via RO before injecting the water into the ground. Both facilities see limited attenuation of NDMA, and NDMA was found in all drinking water wells influenced by the injected water in Orange County. In contrast, NDMA is rapidly attenuated at SAT sites receiving water that has not undergone RO treatment, even though very high concentrations (1,000 ng/L) have been applied to SAT systems in Los Angeles County. The lack of BDOC and nutrients in the waters treated by RO resulted in negligible microbial attenuation during subsurface transport. In Orange County, both NDMA and 1-4 Dioxane were not attenuated and additional advanced treatment after RO is now required since the biological attenuation associated with SAT does not occur. The ability of BDOC to support a diverse microbial community capable of removing CPCs is critical to successful SAT operation.

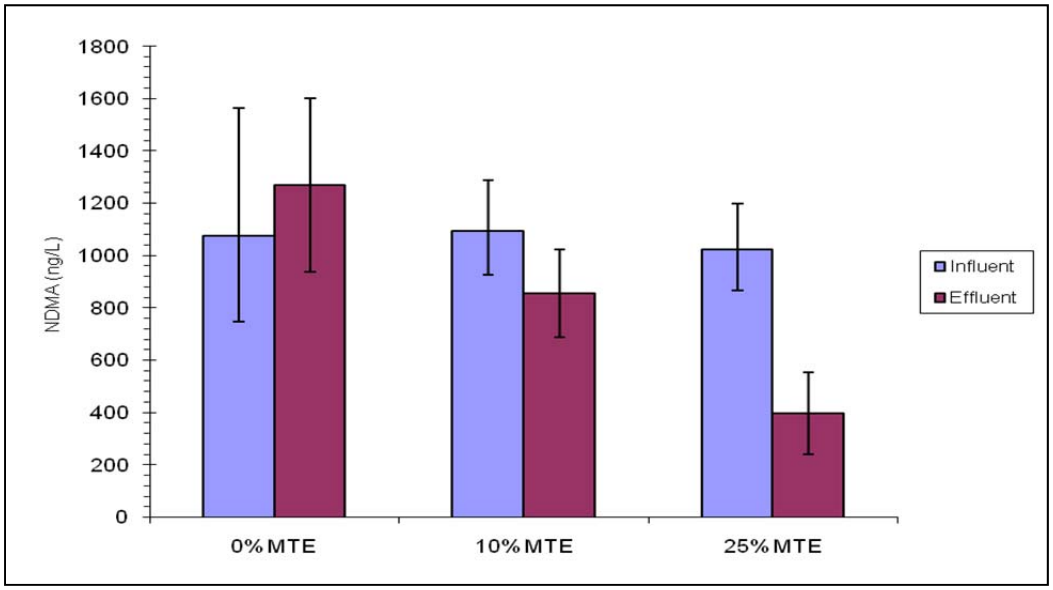

Figure 4-9. N-nitrosodimethylamine (NDMA) concentrations before and after 20 days of SAT

(Source: Nalinakumari, 2010) Drinking water was blended with Mesa Tertiary Effluent (MTE). No removal of NDMA occurred with 0% MTE. Removal of NDMA increased as the percentage of MTE increased. The removal of NDMA correlated with the increase in BDOC concentration.

4.6 Quantitative-Structure Activity Relationship (QSAR) Model Predictions

Prediction of the removal of CPCs during SAT is often done with the use of Quantitative Structure Activity Relationships (QSAR) (WRF-06-18). A QSAR model uses information about the chemical structure of a compound to predict the activity of the compound in different systems. A QSAR model was developed based on a modification of the USEPA model for Persistence, Bioaccumulation and Toxicity. The modifications included the mechanisms by which sorption enhances biodegradation during SAT and the effect of co-metabolism. The model was verified using a set of 32 compounds that had been studied either in SAT systems or

similar model soil systems (Lim and Fox, 2011). After verification, the model was used to analyze over 2,000 compounds obtained from a FDA database of compounds currently being tested for use as pharmaceuticals. The study revealed that the persistence of pharmaceutical compounds being developed should decrease in the future. This is mostly a consequence of the increasing percentage of compounds produced through biotechnology (Lim and Fox, 2012). The percentage of compounds produced through biotechnology should increase from less than 25% to greater than 75% over the next five years.

4.7 Subsurface Travel Times

During SAT, the transformation of organic compounds may be categorized into several different regimes defined as short-term transformations (where relatively fast reactions occur on a time scale of days), and long-term transformations (where recalcitrant compounds continue to transform at slower rates on a time scale of weeks to months) (Fox and Drewes, 2001). Easily biodegradable carbon is transformed within a time scale of days.

Previous studies have characterized the transformation and removal of select CPCs during SAT for travel times ranging from less than one day to more than eight years (Drewes et al., 2003b; Montgomery-Brown et al., 2003; Grünheid et al., 2005; Amy and Drewes, 2007; Massmann et al., 2008; Laws et al., 2011). The results for common classes of CPCs are summarized in Table 4-1. Compounds such as analgesics are rapidly removed even when present at elevated concentrations (Figure 4-10).

Table 4-1. Removal Times during SAT for Common Classes of CPCs

Common Classes of CPCs	Time for Removal During SAT (order of magnitude)	Comments
Analgesics	Days	
Hormones	Days	
Detergent Residuals	Weeks	
Food Additives	Weeks to Months	Sucralose is on the order of years
Insecticides	Months	
Antibiotics	Months	
Flame Retardants	Years	Most are Hydrophobic
Anticonvulsants	Years	

The removal of CPCs in general tends to parallel the removal of dissolved organic carbon. That is, easily biodegradable CPCs, such as caffeine (Young et al., 2008) and 17β-Estradiol, tend to degrade on a time scale of days, while more refractory compounds, such as NDMA and sulfamethoxazole, tend to degrade over a time scale of weeks to months (Dickerson et al., 2008). Persistent compounds such as carbamezapine and primodone can persist for months or years (Figure 4-11) (Clara et al., 2004, Heberer, 2002).

In an effort to determine if a group of compounds could serve as a surrogate for the removal of constituents of concern in SAT systems, compounds were grouped as “good removed”, “intermediate removed” and “poor removed” for travel times of five days and 14 days (Dickerson et al., 2008). The results did not provide clear evidence for the use of a surrogate and the 14-day travel time was sufficient to transform DOC to levels consistent with the refractory nature of

the residual organic carbon. Similar results for alkylphenol polyethoxylates, Ethylenediaminetetracetic acid (EDTA) and Nitrilotri Acetic Acid (NTA) were observed at two different field sites in Arizona (Montgomery-Brown et al., 2003, Yoo et al., 2006).

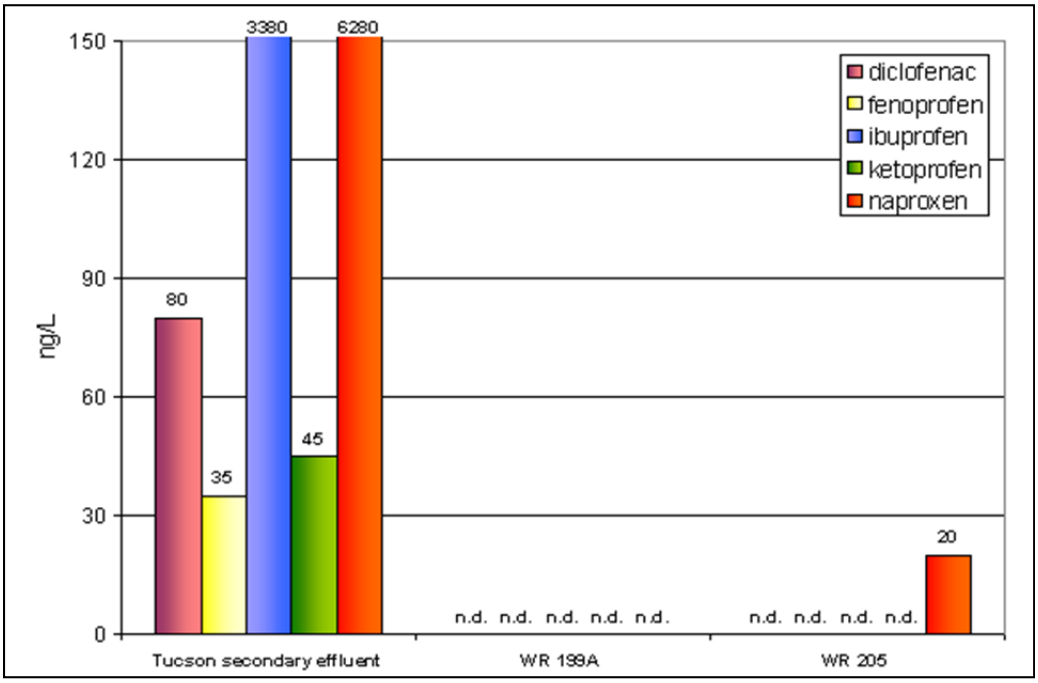

Figure 4-10. The removal of high concentrations of analgesics by SAT

(Source: Drewes, 2003b) WR199A and WR205 are monitoring wells located below the recharge basins with travel times less than two weeks.

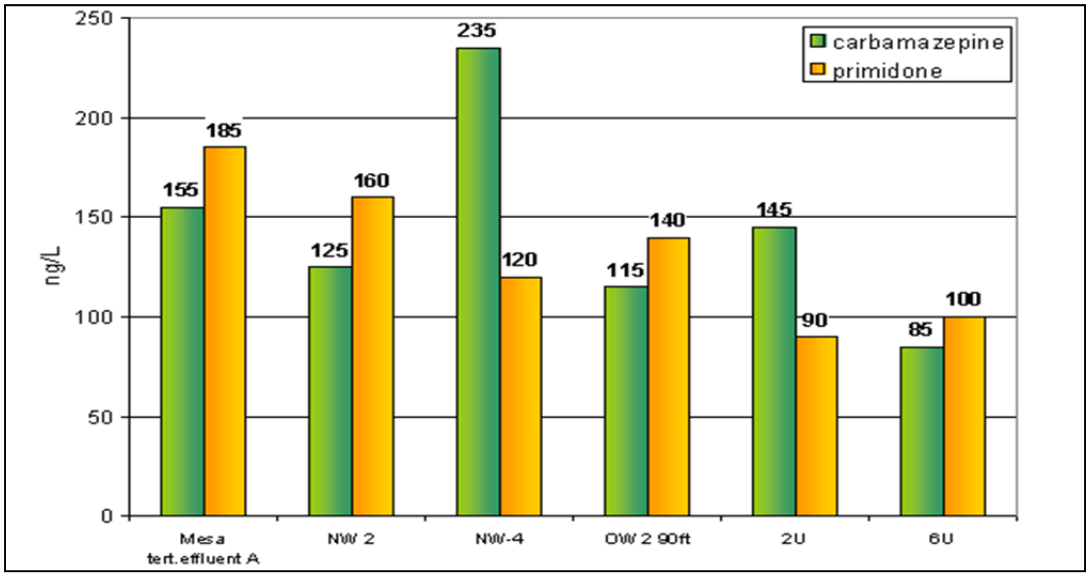

Figure 4-11. The fate of two anticonvulsant pharmaceuticals during SAT

(Source: Drewes, 2003b) The x-axis represents downgradient wells with increasing travel times ranging from 1 to 12 months. Evidence to attenuation of these compounds during SAT is limited.

The fate of anthropogenic compounds that can be detected at µg/L concentrations during SAT has also been studied (Naraswamy et al, 2001). These compounds include food additives such as EDTA, detergent residues that are quantified as Alkylphenol Polyethoxylates, and halogenated organic compounds. Halogenated organic compounds include brominated, chlorinated and iodated organics and they can be measured as Adsorbable Organic Halides (AOX). The majority of these compounds are removed over a time scale of months (Figure 4-12). As can be seen the AOX concentration decreases until it converges with the Adsorbable Organic Iodine (AOI) concentration. This implies that the chlorinated and brominated compounds are removed during SAT and there is a persistent form of organic iodine. This is somewhat surprising since it is commonly known that organic iodine compounds are usually less stable than chlorinated and brominated compounds. Some X-ray contrast agents such as Iopromide contain organic iodine structures that are stable and the persistent organic iodine may be attributed to degradation products of these X-ray contrast agents.

The removal of AOX provides evidence that chlorinated and brominated disinfection byproducts were also removed. This has been verified by the measurment of both trihalomethanes and haloacetic acids in reclaimed water before and after SAT. As part of the study on disinfection byproducts, the trihalomethane formation potential of water after SAT was also determined. It was found that the trihalomethane formation potential of water after SAT was similar to the trihalomethane formation potential of surface waters. The result is consistent with the findings that the majority of DOC that persists in SAT systems is actually natural organic matter. After SAT, the bromide concentration is usually higher as compared to a surface water; thus, the disinfection byproducts that could be formed tend to be more brominated as compared to a surface water.

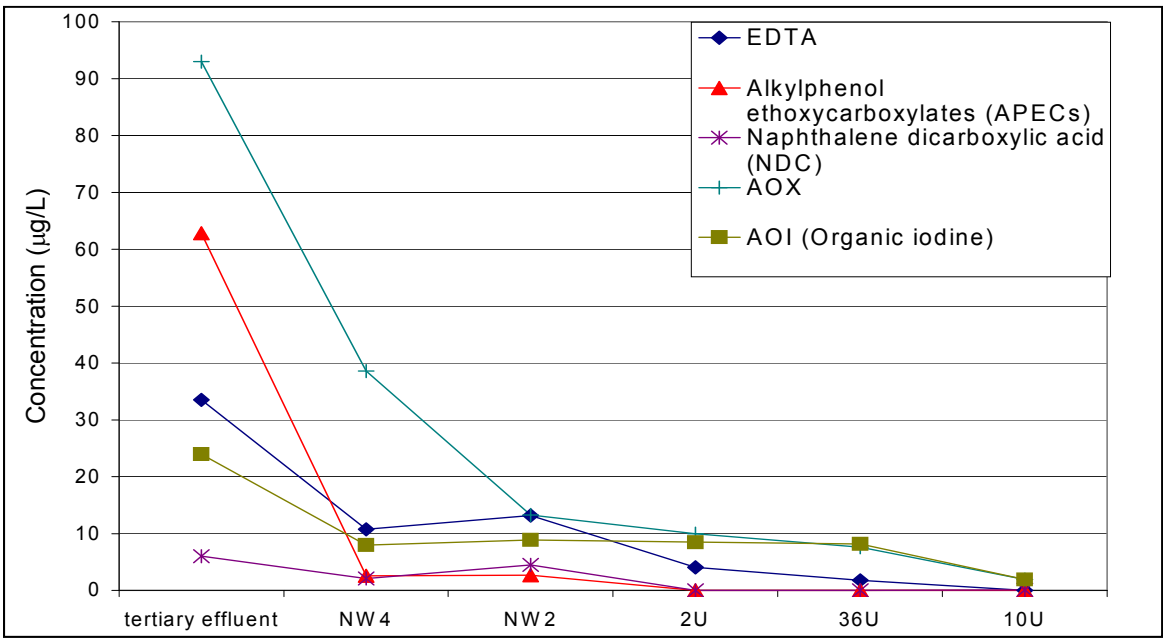

Figure 4-12. Fate of anthropogenic compounds detectable at µg/l concentrations

(Source: Naranaswamy, 2001) The x-axis are downgradient well locations with increasing travel times ranging from 1 to 12 months.

Pathogens are a major concern in all reclaimed water systems, and the highest risk associated with pathogens is ingestion. Recharge basins are open to the environment and efficiently disinfected reclaimed waters that are considered pathogen free can be easily contaminated.

Consequently, concerns over pathogens have resulted in the implementation of travel time requirements for SAT and bank infiltration systems. Since subsurface transport of parasites is unlikely because they are too large to be transported through the aquifer material pore-space, the criteria for developing travel time requirements is based on the potential for virus survival and transport.

Travel time requirements for bank filtration systems in Germany and the Netherlands are 50 days and 60 days, respectively. A bank filtration system that meets the minimum travel time does not require disinfection of the produced (i.e., extracted) water. In California, travel time requirements range from three to 12 months depending on the percentage of reclaimed water at the extraction site. In 2009, Massachusetts adopted a six-month travel time requirement for environmental buffers in indirect potable reuse systems. The retention times required for environmental buffers ranges from 50 days to 12 months. The study by Yates (1985) is often considered the basis for the longer travel time requirements in California as compared to requirements in Europe. Yates (1985) observed virus survival times as long as six months at temperatures below 10^{o}C. During SAT, viruses may be attenuated by sorption, predation and die-off. Yates (1985) focused primarily on die-off and the test conditions did not consider sorption or predation. As the importance of predation in SAT systems has been validated (Toze et al., 2003), the minimum travel time requirement in California has decreased. During the AWWARF (2001) study on SAT, hundreds of wells in California were sampled for enteric viruses. There was no discernable difference between wells impacted by SAT projects and wells that were not impacted by SAT projects. The times established for virus removal are sufficient for transformation of CPCs, as noted earlier in this subsection, and most systems have a significant safety factor with respect to the time required to remove CPCs.

4.8 Aquifer Materials

Most groundwater recharge basins require fairly thick and relatively permeable aquifer deposits. These types of deposits tend to be formed by rivers or glaciers. Theses type of aquifer materials are typically composed of layers of silts, sands and gravels with intermittent clay lenses (Grischek et al, 2002). One hypothesis for the robustness of SAT systems is that when travel time criteria are applied to their design, the surface area contact during subsurface transport is similar in most systems. Since removal mechanisms during subsurface transport are dependent on surface area, systems with similar amounts of surface area can provide similar levels of removal.

Makam and Fox (2009) considered the relationship between surface area and travel time in aquifers commonly associated with SAT systems. For a specific hydraulic gradient and travel time, the surface area in aquifers containing silt, sand and gravels varied by less than a factor of 2.5 (Figure 4-13). The commonality of aquifer materials and the use of travel time criteria appear to be the primary reason for similar performance of SAT systems throughout the world.

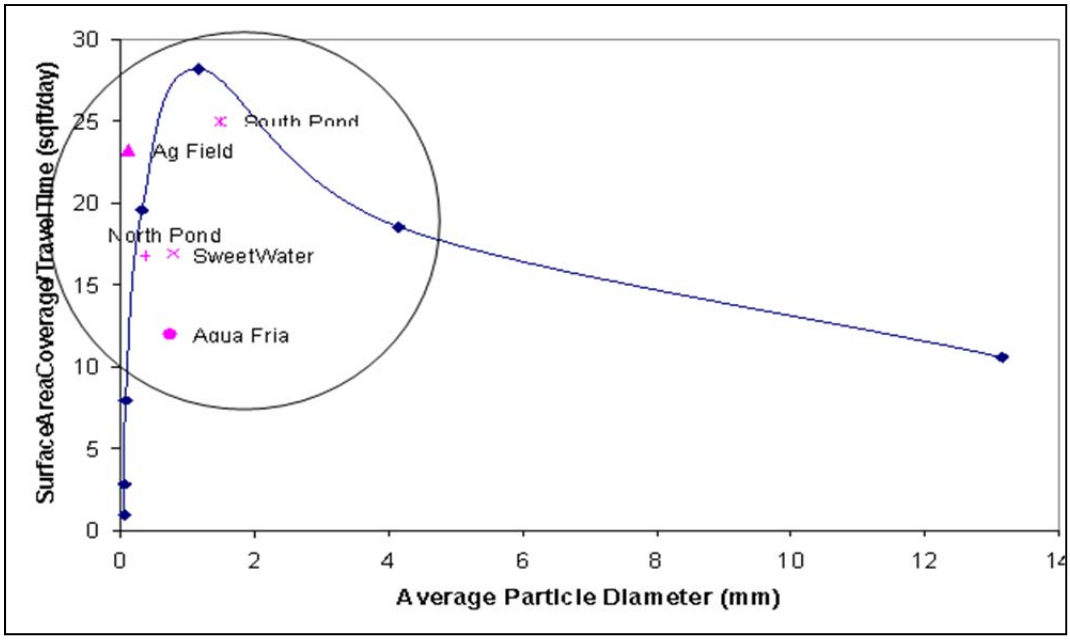

Figure 4-13. Surface area normalized to travel time for common aquifer materials (silts, sands, and gravels) for a specific hydraulic conductivity

(Source: Makam and Fox, 2009) The data points are samples from actual or proposed SAT sites. The range of normalized surface is less than a factor of 2.5 for common aquifer materials.

4.9 Vadose Zone versus Saturated Zone

No correlation between vadose zone depth and treatment efficiency exists when comparing different SAT sites. When comparing the Mesa Northwest Water Reclamation Plant with the Tucson Sweetwater Underground Storage and Recovery Facility, the post-SAT water was the same with respect to CPCs. The Mesa facility has a vadose zone of less than 30 feet and saturated conditions develop rapidly during infiltration because of clay lenses in the vadose zone. The Tucson facility has a vadose zone over 100 feet deep and unsaturated conditions exist in the vadose zone. The existence of aerobic conditions in the vadose zone can enhance the rate of attenuation but the oxygen content and water quality is reduced after a time period of several weeks.

As described in Section 4.3, when aerobic and anoxic conditions are compared, the kinetics under aerobic conditions are faster on a time scale of several days, but the total removal is similar after 20 days, which is a short time for an SAT system. Poorly treated wastewater with high biological oxygen demand can cause anaerobic conditions which will completely alter the kinetics of organic compound removal. However, drying cycles will return vadose zone soil to aerobic conditions. In Tucson, the reclaimed water contains much higher concentrations of organic carbon and ammonia as compared to the Mesa site, such that the oxygen demand at the Tucson site is 10-20 times greater than the Mesa site. Aerobic conditions in the upper vadose zone are returned at both sites during drying cycles. At Mesa, the loading rates are lower because infiltration rates are reduced by the presence of clay lenses. The clay lenses result in saturated flow conditions occurring almost immediately after a wetting cycle is initiated. The low oxygen demand in the water at the Mesa site result in aerobic conditions being maintained in the top five feet of the vadose zone even with the saturated flow conditions. If the loading rate could be increased at the Mesa site, anoxic conditions might develop faster but

removal would continue to be the same at downgradient monitoring wells as the redox conditions will not effect removal at longer time scales. Many bank filtration systems in Europe are primarily anoxic and the observed removal is similar to SAT systems.

Requirements to monitor in the groundwater mound directly below a recharge basin do not effectively measure SAT performance because the samples only consider removal in the vadose zone. Transport under unsaturated conditions can also be highly variable and are dependent on degree of saturation, previous drying times, temperature and other factors. One study determined that the transport time in a vadose zone could vary from 20 days to less than one day (Park et al., 2006), For these reasons, monitoring at multiple depths downgradient is recommended to fully characterize water quality improvements during SAT.

A vadose zone may enhance nitrogen transformations if ammonia removal is desired. Nitrification requires oxygen, and reaeration of the soil during a drying cycle is necessary to nitrify adsorbed ammonia. Denitrification and anaerobic ammonia oxidation can occur under anoxic conditions deep in the vadose zone or in the saturated zone.

4.10 Temperature

The effect of temperature on SAT systems has primarily been studied with respect to virus survival. Longer virus survival was observed under laboratory conditions at lower temperatures and this would be expected. The laboratory studies were purely focusing on the ability of a virus to survive and did not consider the other removal mechanisms for virus removal in SAT systems. As enteric viruses cannot reproduce in SAT systems, a major removal mechanism is biodegradation during SAT. This has been verified for viruses in SAT systems even at low temperatures.

Groundwater temperatures tend to be independent of surface water temperatures as the groundwater is insulated from changes in climate. Berlin, Germany has relied on bank filtration for its drinking water supply for over 70 years. A significant portion of the surface water used is treated wastewater that is discharged into the surface water. When comparing the removal of DOC and CPCs in the bank filtration systems in Berlin with SAT systems in the Southwestern United States, the remove of DOC and CPCs is quite similar on a time scale of two months. This similarity exists even though the climates are considerably different. The climate in Berlin is consistently colder in the winter months as compared to the climate in the Puget Sound during the winter months.

4.11 Dilution

As water infiltrates to the saturated zone, mounding of groundwater occurs in the vicinity of a recharge basin. Over longer time periods, a plume of reclaimed water will develop that might or might not be captured by wells. Since vertical mixing is limited in aquifers, the upper portion of the aquifer can contain reclaimed water while the lower portion of an aquifer can remain native groundwater. Therefore, most production wells using water originating from a SAT system will pump a mixture of reclaimed water and native groundwater. The percentage of reclaimed water recovered from an SAT system is most often determined by an intrinsic tracer. An intrinsic tracer is an inert compound that is present in the reclaimed water that is not attenuated. Simple intrinsic tracers that can be used are common anions, cations or ionic signature. Sodium, bromide, iodine, chloride and sulfate are all common examples of intrinsic tracers that can be used to determine dilution in either production wells or in samples obtained during monitoring.

Attenuation cannot be attributed specifically to dilution without first understanding the degree of dilution that exists in a given groundwater system.

4.12 Persistent Compounds

While the majority of CPCs are attenuated during SAT, it is well known that certain compounds are persistent and resist attenuation even during SAT. Carbamezapine and primodone, both antiepileptic pharmaceuticals, are known to persist under almost all environmental conditions. It has been suggested that carbamezapine could be used as an anthropegenic marker (Clara et al., 2004). Carbamezapine has also been used as an intrinsic tracer to characterize the dilution of reclaimed water in SAT systems. Another class of persistent compounds includes flame retardants that are water soluble. This includes compounds like tri(2-chloroethyl) phosphate (TCEP). A list of compounds and their relative persistence studied by Dickerson et al. (2008) is presented in Table 4-2. In order for a compound to persist in an SAT system it must have a relatively low K_{ow} so that it will not be effectively adsorbed. In addition, the compound must resist biodegradation including co-metabolism. Since co-metabolism can occur with non-specific oxygenase enzymes, persistent compounds tend to be difficult to oxidize. This is particularly true for flame retardants since they are designed to resist oxidation.

Table 4-2. Summary of relative biodegradation of various compounds in SAT systems
(Adapted from Dickerson, et al, 2008)

Constituent of Concern	Log Kow	Persistence
17β-Estradiol	4.03	Low
Caffeine	-0.07	Low
Carbamezapine	2.45	High
DEET	2.18	Medium
Dilantin	2.47	Medium
Estrone	3.13	Low
Ibuprofen	3.97	Low
Sulfamethaxozle	0.89	Medium
Triclosan	4.76	Medium
Tri(2-chloroethyl) phosphate - TCEP	1.44	High

In 2012, the California State Water Resources Control Board (SWRCB)[2] endorsed a concept for monitoring SAT systems. This concept followed the recommendations of a Science Advisory Panel as a suitable monitoring approach to ensure proper performance of SAT operations regarding the removal of trace organic chemicals (Anderson et al., 2010). The SWRCB suggested a combination of appropriate surrogate parameters, and health-based parameters and performance-based indicator chemicals for monitoring of SAT projects. Monitoring requirements suggested by Anderson et al. (2010) are summarized in Table 4-3. It is interesting to note that the health based indicators are all compounds that should be effectively removed by SAT. Sucralose is persistent during SAT and is one of the persistent compounds that can be present at µg/L concentrations since it is widely used as an artificial sweetener.

[2] State Water Resources Control Board (2012). California Water Recycling Policy – Amendment A: Requirements for Monitoring Constituents of Emerging Concern for Recycled Water (Draft). April 23, 2012. Sacramento, CA.

Table 4-3. Health-based and performance-based CPC indicators and performance surrogates for SAT practices suggested by the Science Advisory Panel
(Adopted from Anderson et al., 2010)

Reuse Practice	Health-based Indicator	MRL (ng/L)	Performance-based Indicator	Expected Removal[8]	MRL (ng/L)	Surrogate	Method	Expected Removal[8]
SAT	17 β - estradiol[1]	1	Δ gemfibrozil[5]	>90%	10	Δ ammonia	SM	>90%
	Triclosan[2]	50	Δ DEET[6]	>90%	10	Δ nitrate	SM	>30%
	Caffeine[3]	50	Δ Caffeine[3]	>90%	50	Δ DOC	SM	>30%
	NDMA[4]	2	Δ iopromide[5]	>90%	50	Δ UVA	SM	>30%
			Δ Sucralose[7]	<25%	100			

[1]Steroid hormones; [2]Antimicrobial; [3]Stimulant; [4]Disinfection byproduct; [5]Pharmaceutical residue; [6]Personal care product; [7]Food additive; [8]travel time in subsurface two weeks and no dilution, see details in Drewes *et al*., 2008; SM – Standard Methods; MRL – Method reporting level

4.13 SAT Research Focus Areas (Current and Emerging)

Current research on SAT systems is focusing on how to integrate SAT systems more effectively into urban water management. For example, the California Department of Public Health has recognized that SAT is generally safe and would prefer to find simpler ways to regulate SAT sites such that SAT can be more widely and effectively used. Research to support this includes methods to more effectively regulate and monitor SAT systems to ensure public safety without having to continuously monitor for every possible new contaminant. One aspect of this research is to identify a surrogate or group of surrogates that can effectively be used to determine that SAT has treated the water to the best extent possible (as described in the previous section). Another aspect of this research is to clearly define the potential risks associated with SAT by determining factors such as drinking water equivalent levels. Finally, the development of models that can be used to accurately predict the performance of SAT systems under a variety of conditions is another area of research. If accurate predictive models can be developed and verified, the need to conduct extensive monitoring can be reduced and planners can begin to integrate SAT systems into long-term water resource plans with confidence.

5.0 Relative Risks Associated with Reclaimed Water

People often question if reclaimed water is “safe”, implying that to be safe the use of reclaimed water poses no risk of harm to human health or the environment. This is a challenging question to answer, as there are many ways to explore the concepts of risk and safety. NRC 2012 notes: “An evaluation of the adequacy of public health and ecological protection rests upon a holistic assessment of multiple lines of evidence, such as toxicology, epidemiology, chemical and microbial analysis, and risk assessment”. Of these tools that are available to characterize risk, currently decisions regarding public health and environmental protection are based on “measurement of chemical and microbiological parameters and the application of the formal process of risk assessment” (NRC 2012). This is because of the limitations of toxicological testing and population-level epidemiological studies that exist regarding impacts of reclaimed water.

Risk assessment is not a focus of this document; therefore, only a very brief summary is provided below. The reader is directed to NRC 2012, and the associated studies referenced

therein, for more detail. The intent of this section is to describe the general approach to risk assessment and the way in which NRC 2012 elected to comprehensively consider the various risks posed by multiple types of water supply, including those involving reclaimed water.

5.1 Risk Assessment – Human Health

Historically the paradigm for risk analysis regarding human health in the US has been divided into risk assessment and risk management. This framework has evolved over time into one put forth by NRC in 2009, as presented in Exhibit 5-1. Key elements of Phase II of this paradigm (Risk Assessment) include the following:

- Hazard Identification. The determination of whether exposure to a given constituent can cause the increase in the incidence of a health condition.
- Exposure Assessment. The level of contact between a person and a substance. With regard to water-borne constituents, this is the product of substance concentration (in a medium, like water) and the amount of the medium to which a person is exposed.
- Dose-Response Assessment. Characterizing the relationship between a given dose of a substance and the incidence of an adverse health effect. Dose-response relationships are the basis for risk assessments used in establishing drinking water standards.
- Risk Characterization. At this stage, the understanding gained from the prior three elements is integrated to form an overall conclusion about the risk. There exist many forms of summary measures of risk, such as Reference Doses (RfD), Acceptable Daily Intake (ADI), and Thresholds of Toxicological Concern (TTCs).

While health risks are very difficult to fully characterize, the process embodied by this paradigm provides approaches to estimating risks for various reclaimed water uses.

Exhibit 5-1. Risk Paradigm
(From: NRC 2012)

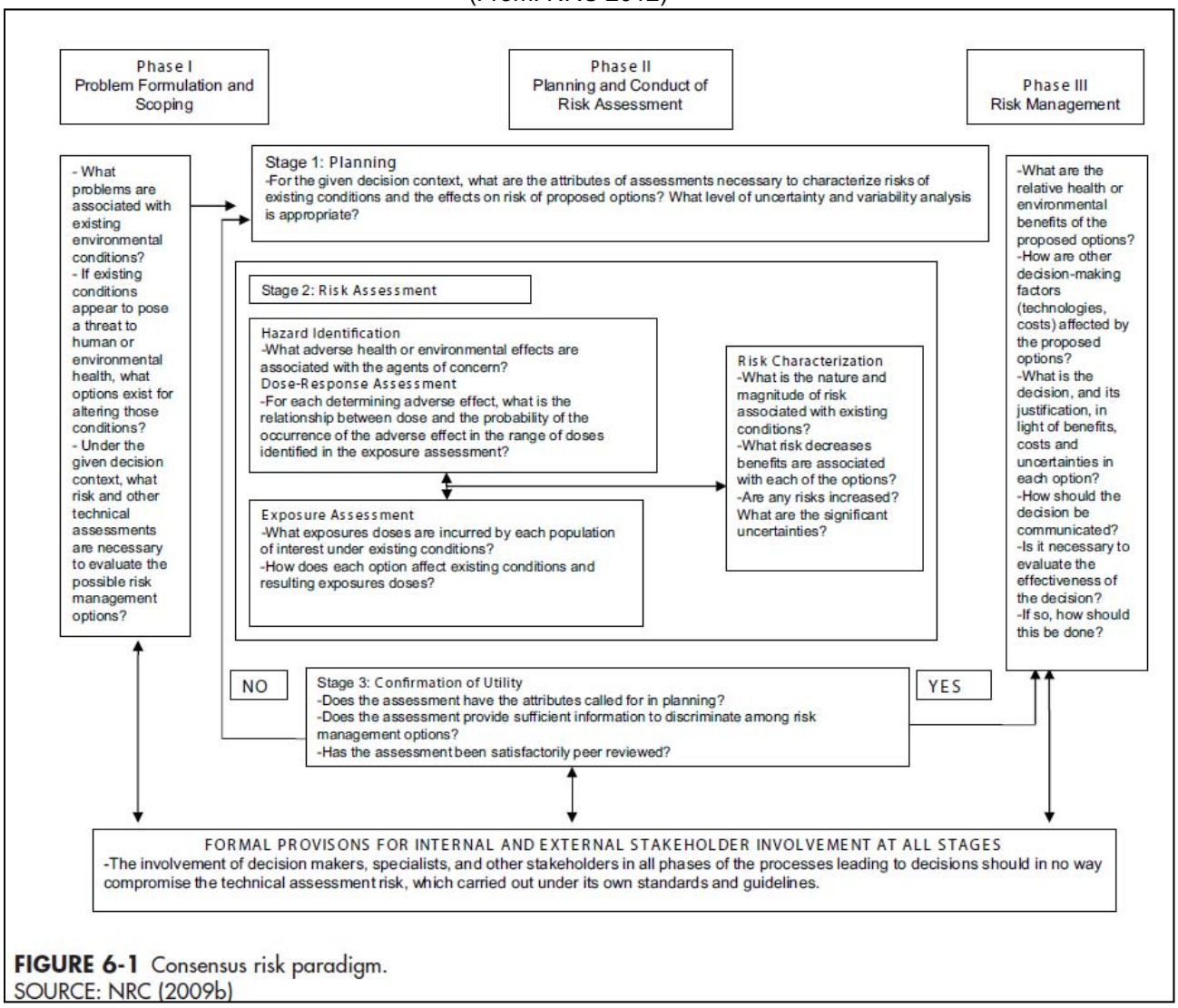

FIGURE 6-1 Consensus risk paradigm.
SOURCE: NRC (2009b)

5.2 Risk Exemplar

Due to the complexities of risk assessment, NRC 2012 developed a "risk exemplar" to compare the relative risks from exposure to pathogens and CPCs between a conventional water supply scenario and potable reuse scenarios. Though not a direct reflection of the situation faced by LOTT currently in Thurston County, this hypothetical analysis is informative in terms of understanding relative risks between various constituents, and between water supplies that include reclaimed water versus those that do not.

The three scenarios considered in the NRC analysis are:

- Scenario 1: De facto reuse (common surface water supply). This involves a conventional drinking water treatment plant receiving surface water supply, five percent of which is comprised of secondary treated wastewater (from an upstream discharge).

- Scenario 2: Soil Aquifer Treatment. This involves a deep drinking water supply well that is withdrawing groundwater from an aquifer fed by reclaimed water that has been generated from a process of secondary wastewater treatment, nitrification (and partial denitrification), granular media filtration, no disinfection, and soil aquifer treatment (via recharge basins).
- Scenario 3: MF/RO/UV/Direct Aquifer Recharge. This involves a deep drinking water supply well that is withdrawing groundwater from an aquifer fed by reclaimed water that has been generated from a process of secondary wastewater treatment, chloramination, microfiltration, reverse osmosis, and AOP using UV and hydrogen peroxide, and soil aquifer treatment (via direct injection into the saturated zone)

As such, both Scenarios 2 and 3 represent potable reuse examples, which are then compared to de facto potable reuse (Scenario 1). The exemplar considered a broad range of contaminants including common pathogenic bacteria, viruses, and protozoa, as well as CPCs at assumed typical levels present under the conditions represented in the three scenarios.

The results of the risk exemplar are summarized in Exhibits 5-2 and 5-3.

Exhibit 5-2 displays the relative risk of someone becoming ill by ingesting the drinking water from each scenario. The results indicate that the potable reuse scenarios have lower risks than the de factor reuse scenario. Virus-related risk is substantially reduced in both SAT examples. The risks related to bacteria and protozoa are more significantly reduced where MF/RO/UV is utilized.

Exhibit 5-3 summarizes the risk results associated with all 24 organic compounds (CPCs) considered. This table provides the Risk-Based Action Level (RBAL) for each chemical, and also displays the exemplar results in the form of a Margin of Safety (MOS) that is calculated for each chemical in each scenario.

The RBALs represent benchmark values for potential lifetime health risks (related to ingestion of a particular chemical) or existing chemical-specific action levels. These include EPA Maximum Contaminant Levels (MCLs), EPA health advisories, World Health Organization Acceptable Daily Intakes (ADIs), etc.

A MOS is calculated by dividing a chemical's RBAL by its concentration in water. Thus, a MOS greater than 1 (meaning the RBAL is larger than the assumed concentration) indicates that there is "unlikely to be a significant health risk, even after a lifetime of exposure to an individual chemical" (NRC 2012). Furthermore, the higher the MOS, the lower the risk. A MOS less than 1 is considered a potential concern for human health (in effect meaning there is no margin of safety relative to that particular chemical). In some cases, the assumed concentration of a chemical was below the detection limit. In such instances, the concentration in the MOS calculation was given to be the detection limit. Thus, the actual MOS is likely higher than the number depicted in the table (hence the ">" symbols associated with some values).

The only chemical with a resulting MOS less than 1 was NDMA, at a MOS of 0.4 for all scenarios. Although NDMA was calculated to be below the detection limit (2 ng/L) in all cases, the detection limit is greater than the established lifetime cancer risk used in the analysis (0.7 ng/L, the EPA's health advisory level for this compound). As such the MOS was calculated as less than 1, and is the same for all scenarios.

Aside from NDMA, the results do not indicate that any chemical poses a health risk of concern in any of the scenarios. Although this is but one analysis and contains multiple assumptions specific to the defined scenarios, the exercise demonstrates that properly designed and operated potable reuse systems are capable of providing protection from viruses and CPCs similar to what the public experiences from many drinking water systems today.

Exhibit 5-2. Relative Risk of Illness
(From: NRC 2012)

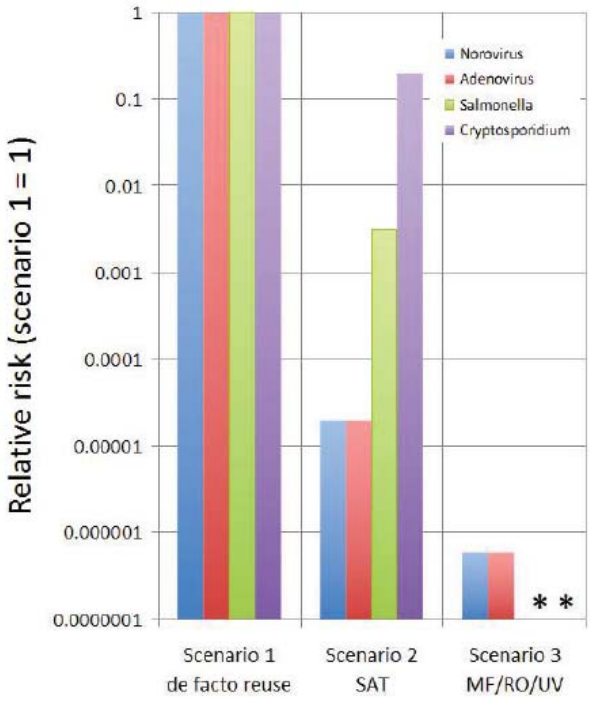

FIGURE 7-2 Relative risk of illness (gastroenteritis) to persons drinking water from each of the reuse scenarios relative to de facto reuse (Scenario 1). The smaller the number, the lower the relative risk of the reuse applications for each organism. For example in Scenario 2, the risk of illness due to *Salmonella* is estimated to be less than 1/100th of the risk due to *Salmonella* in Scenario 1.
NOTES: *The risks for *Salmonella* and *Cryptosporidium* in Scenario 3 were below the limits that could be assessed by the model.

Exhibit 5-3. Margins of Safety
(From: NRC 2012)

TABLE 7-1 Summary of Margin of Safety (MOS) Estimates for the Three Scenarios Analyzed by the Committee

Chemical	Risk-Based Action Level[a]	MOS Scenario 1, de Facto Reuse	MOS Scenario 2, SAT, No Disinfection	MOS Scenario 3 MF/RO/UV
Nitrosamines				
NDMA	0.7 ng/L	>0.4	>0.4	>0.4
Disinfection byproducts				
Bromate	10 µg/L	N/A	N/A	> 2
Bromoform	80 µg/L	27	160	>160
Chloroform	80 µg/L	16	80	16
DBCA	60 µg/L	>60	>60	>60
DBAN	70 µg/L	>54	>140	N/A
DBCM	80 µg/L	>80	N/A	>160
DCAA	60 µg/L	12	>60	>60
DCAN	20 µg/L	>20	>20	N/A
HAA5	60 µg/L	6	12	12
THM	80 µg/L	2.7	16	8
Pharmaceuticals				
Acetaminophen	350,000,000 ng/L	>350,000,000	>350,000,000	>35,000,000
Ibuprofen	120,000,000 ng/L	>120,000,000	56,000,000	>280,000,000
Carbamazepine	186,900,000 ng/L	10,000,000	1,200,000	>190,000,000
Gemfibrozil	140,000,000 ng/L	8,600,000	2,300,000	>140,000,000
Sulfamethoxazole	160,000,000 ng/L	>80,000,000	720,000	>160,000,000
Meprobamate	280,000,000 ng/L	17,000,000	8,800,000	>930,000,000
Primidone	58,100,000 ng/L	10,000,000	450,000	>58,000,000
Others				
Caffeine	70,000,000 ng/L	3,500,000	>70,000,000	>23,000,000
17-β Estradiol	3,500,000 ng/L	>35,000,000	>35,000,000	>35,000,000
Triclosan	2,100,000 ng/L	>3,500,000	840,000	>2,100,000
TCEP	2,100,000 ng/L	>84,000	5,800	>210,000
PFOS	200 ng/L	17	4	>200
PFOA	400 ng/L	36	19	>80

NOTES: > indicates that the assumed concentration was below detection, and only an upper limit on the risk calculation was determined. See Appendix A for further detail. [a]Sources of the risk-based action limits are provided in Table A-11 of Appendix 11.

5.3 Risk Assessment – Ecological

There are many questions regarding the risk of CPCs to the environment, due to the lack of associated environmental fate and effects information. A key challenge is attempting to understand the effects of mixtures of bioactive CPCs that may be present in water. In some cases, the resultant toxicity of a mixture may be greater than the sum total of the toxicity of individual components. In other cases, however, the combined toxicity may be equal to or less than that of the individual elements.

As with human health risk assessments, there are numerous methods that can be used for this purpose in an ecological context. These methods include effluent toxicity testing and newer approaches such as in vivo biomarkers, in vivo bioassays, and gene expression profiling.

6.0 Summary

6.1 "State of the Science" Regarding Reclaimed Water and Soil Aquifer Treatment

Wastewater, treated wastewater, and reclaimed water contain a broad spectrum of biological, inorganic, and organic constituents that present various levels of risk to public health and the environment. There are numerous combinations of processes, including engineered processes (such as those employed at conventional wastewater treatment facilities) and managed natural treatment processes (such as Soil Aquifer Treatment, or SAT), used in wastewater treatment and reclamation that remove these constituents to varying degrees. Based on a survey of existing literature, this technical memorandum has provided an overview of these treatment processes and their effectiveness in the removal of contaminants from wastewater. This "State of the Science" has focused particularly on summarizing the current scientific understanding of the interactions between reclaimed water and groundwater, with an emphasis on compounds of potential concern (CPCs).

The following are key summary points extracted from earlier sections of the technical memorandum:

- CPCs represent a small portion of the dissolved organic carbon that is present in wastewater, treated wastewater, and reclaimed water. These are chemicals that originate from industrial and domestic products and activities, are excreted by humans, or are chemical by-products formed during water or wastewater treatment processes. Categories of CPCs include pharmaceuticals, personal care products, household chemicals, food additives, and pesticides. Most CPCs are observed in treated wastewater and reclaimed water, as well as drinking water, at the nanogram per liter level (parts per trillion).
- Wastewater and reclaimed water treatment processes have varying effectiveness at removing CPCs. Conventional secondary wastewater treatment (i.e., activated sludge) has a percent removal of more than 90% for some CPCs, but less than 10% for others. Advanced treatment in the form of reverse osmosis has a percent removal of more than 95% for most CPCs, with one exception being NDMA (having a removal rate of 25-50%). Soil aquifer treatment has been observed to have a percent removal of more than 90% for most CPCs, with specific compounds persisting for long times in SAT systems. Such persistent compounds include carbamazepine (an anti-epileptic drug), sulfamethoxazole (an antibiotic), flame retardants, and sucralose (a food additive).
- The removal of contaminants, including CPCs, by SAT has been well documented and the mechanisms by which removal occurs have been determined. In comparison to a wastewater treatment plant, the long residence times and large surfaces areas associated with SAT provide an ideal environment to sustain contaminant removal by biodegradation, which serves as the primary treatment mechanism in such systems. Since most SAT systems are designed based on travel time criteria and because aquifer materials do not vary significantly, the performance of most SAT systems is similar.
- Travel time requirements are key design criteria for SAT systems. The approach to developing travel time requirements has been largely based on virus survival as transport of viruses represents one of the largest health risks associated with SAT systems. Travel time requirements range from 50 days to 12 months. These minimum

travel time requirements not only provide a barrier to viruses, but also provide sufficient time for the removal of most CPCs.

- Because of the limited amount of toxicological testing and the lack of population-level epidemiological studies that exist regarding human health impacts of reclaimed water, recent approaches of risk assessment regarding reclaimed water and specifically CPCs has involved comparing the risk from water produced by potable reuse projects (i.e., systems producing reclaimed water that is introduced into drinking water supplies, such as through recharge of drinking water aquifers) with the risk associated with water supplies that are presently in use. Such an approach documented in NRC 2012 explores two potable reuse scenarios that incorporate groundwater recharge: one involving soil aquifer treatment (through surface percolation of filtered secondary effluent), and the other involving direct injection of water having undergone reverse osmosis and advanced oxidation). The findings suggest that "…the risk from the selected chemical contaminants in the two potable reuse scenarios does not exceed the risk in common existing water supplies." Furthermore, the NRC analysis concludes that "these results demonstrate that following proper diligence and employing tailored advanced treatment trains and/or natural engineered treatment, potable reuse systems can provide protection from trace organics [CPCs] comparable to what the public experiences in many drinking water supplies today" (NRC, 2012).
- Compared to human health impacts, less is understood regarding potential ecological impacts of CPCs. A key challenge is attempting to understand the effects of mixtures of bioactive CPCs that may be present in water. In some cases, the resultant toxicity of a mixture may be greater than the sum total of the toxicity of individual components. In other cases, however, the combined toxicity may be equal to or less than that of the individual elements. This is an area receiving increased attention by the scientific research community.

6.2 Identified Research Needs

Even given the extensive body of scientific literature that exists regarding reclaimed water and the removal mechanisms that can be utilized in various treatment processes, there remain gaps in the current understanding of the potential risks posed by reclaimed water. This is particularly so in the context of indirect and direct potable reuse systems, which represent the direction in which the industry is heading. A summary of research priorities is provided in NRC 2012, reflecting these gaps. As summarized in Exhibit 6-1, these identified priorities are organized in two main categories: 1) health, social, and environmental issues; and, 2) performance and quality assurance. Notably missing are research priorities related to treatment technology. The authors of NRC 2012 note that although there is room for improvement, there are no identified technological challenges that should prevent the use of reclaimed water to aid in addressing the nation's water supply needs.

Exhibit 6-1. NRC Summary of Research Priorities

(From: NRC 2012)

BOX 11-1
Summary of Research Priorities

These research areas hold significant potential to advance the safe, reliable, and cost-effective reuse of municipal wastewater where traditional sources are inadequate. They are not prioritized here.

Health, Social, and Environmental Issues

1. Quantify the extent of de facto (or unplanned) potable reuse in the United States.
2. Address critical gaps in the understanding of health impacts of human exposure to constituents in reclaimed water.
3. Enhance methods for assessing the human health effects of chemical mixtures and unknowns.
4. Strengthen waterborne disease surveillance, investigation methods, governmental response infrastructure, and epidemiological research tools and capacity.
5. Assess the potential impacts of environmental applications of reclaimed water in sensitive ecological communities.
6. Quantify the nonmonetized costs and benefits of potable and nonpotable water reuse compared with other water supply sources to enhance water management decision making.
7. Examine the public acceptability of engineered multiple barriers compared with environmental buffers for potable reuse.

Treatment Efficiency and Quality Assurance

8. Develop a better understanding of contaminant attenuation in environmental buffers.
9. Develop a better understanding of the formation of hazardous transformation products during water treatment for reuse and ways to minimize or remove them.
10. Develop a better understanding of pathogen removal efficiencies and the variability of performance in various unit processes and multibarrier treatment and develop ways to optimize these processes.
11. Quantify the relationships between polymerase chain reaction (PCR) detections and viable organisms in samples at intermediate and final stages.
12. Develop improved techniques and data to consider hazardous events or system failures in risk assessment of water reuse.
13. Identify better indicators and surrogates that can be used to monitor process performance in reuse scenarios and develop online real-time or near real-time analytical monitoring techniques for their measurement.
14. Analyze the need for new reuse approaches and technology in future water management.

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