Water Reuse for Augmentation of Water Supply

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Introduction

Water is indispensable to human life. However, with the increasing scarcity of freshwater resources and increased water demand, the sustainability of water supply is becoming increasingly jeopardized. Consequently, reuse of wastewater is becoming a more reasonable choice for balancing water deficiencies. Approximately 1,500 water reuse facilities exist in the United States (Awad. 2007); Five to seven % of wastewater is currently reused. While it assists in mitigating the shortage of water, reuse of wastewater leads to an important issue, i.e., the water quality being produced. Water quality ultimately impacts the social acceptability of any wastewater reuse practice. Therefore, development and application of appropriate treatment technologies to meet the requirements of water quality are critical to the success of wastewater reuse.

On a global scale, the increase in water reuse is due to a number of factors including rising water demands, finite water resources, and regulatory and political pressure. Rising water demands are being caused by demographic, economic and urban growth. Finite water resources are causing a need for water reuse as a result of nearby water sources often being rare and vulnerable; remote sources can be costly to develop**.** Regulatory and political pressures are requiring water agencies to limit the discharge of wastewater effluent. Further, it is becoming increasingly difficult to construct freshwater impoundments due to the environmental issues.

There are two general types of water reuse, direct and indirect. Direct reuse refers to the form of reuse characterized by transport of the reclaimed water via pipes or canals. Indirect reuse is the use of natural water bodies of water (usually rivers/ streams, but also lakes/reservoirs and aquifers) to transport and/or purify reclaimed water.

The purpose of this paper is to discuss selected issues on the application reclaimed water to augment water supplies. . Uses of reclaimed water, major pollutants of concern, and, membrane technologies are presented. Additionally, two case studies are provided.

<u>Uses of Reclaimed Water</u>

Reclaimed wastewater has been used for a variety of non-potable applications, including landscape and agricultural irrigation, industrial process water, power plant cooling water, toilet

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flushing, car washing, augmentation of recreational water bodies, fire protection, commercial cleansing, construction, etc. (AWWA/WEF 1998). One of the most significant uses of wastewater or wastewater effluents is agricultural reuse (Bitton 2005). The advantages of agricultural wastewater reuse include high concentrations of nutrients (reducing fertilizer need), decrease in consumption of potable water supply, and additional treatment of wastewater pollutants [e.g., PPCPs and EDCs (Ternes et al. 2007)] in soil before they reach water bodies.

There are many different non – potable uses for reclaimed water, each with its own list of water quality issues of concern, as noted below.

- Agricultural
  - Total dissolved solids, SAR, boron, chloride, chlorine and SS
- Landscaping/Single Family Homes
  - Total dissolved solids, SAR, boron, chloride, chlorine, SS and odors
- Toilets and Urinal Flushing
  - Suspended solids, color and odor
- Water Features
  - Nutrient and color
- Cooling Towers
  - Nutrients, total dissolved solids, suspended solids, chlorides, odor, hardness and selected bacteria
- Textile Mill
  - Color, inorganics, chlorine and odor
- Cement Manufacturers
  - Suspended solids and inorganics
- Wetland Enhancements
  - Nutrients

There has been an increasing interest in using reclaimed wastewater as potable water source. Indirect potable water reuse has been employed around the world. With indirect reuse, the reclaimed wastewater can be recharged to surface or groundwater system that is ultimately employed as a potable water supply (AWWA/WEF 1998).

Table 1 lists the 22 largest U.S. Reuse Programs.

Table 1: Major Water Reuse Programs in the United States

- Orange County Water District
- Central/West Basin
- Metropolitan Water District
- San Jose
- Los Angeles County Sanitation District
- San Diego County
- Irvine Ranch
- Dublin San Ramon
- East Bay Municipal Utility District
- Orlando
- Scottsdale
- Phoenix
- San Antonio
- El Paso
- Tarrant Regional
- St. Petersburg
- Pinellas County
- King County (WA)
- Austin
- Santa Rosa
- UOSA (VA)
- Southwestern Nevada Water Authority/Las Vegas Valley Water District

Regulations and guidelines vary depending on the type of reuse. Indirect potable reuse has the most stringent guidelines with agricultural reuse on non-food crops having the least stringent ones, as shown in Table 2.

Table 2: Stringency of Regulations and Guidelines in the United States from Most to Least Stringent

Indirect Potable Reuse	Most Stringent
Agricultural Reuse on Food Crops	
Unrestricted Recreational Reuse	
Unrestricted Urban Irrigation Reuse	
Restricted Urban Irrigation Reuse	
Restricted Recreational Reuse	
Industrial Reuse	
Environmental Reuse	
Agricultural Reuse on Non-food Crops	Least Stringent

Table 3 lists Reuse Applications and the Number of States with Guidelines

Table 3: States with Reuse Guidelines (2004 Guidelines for Water Reuse, EPA/625/R-04/108)

Type of Reuse	**Number of States**
Unrestricted Urban	28
Restricted Urban	34
Agricultural (Food Crops)	21
Agricultural (Non-food Crops)	40
Unrestricted Recreational	7
Restricted Recreational	9
Environmental (Wetlands)	3
Industrial	9
Groundwater Recharge (Nonpotable Aquifer)	5
Indirect Potable Reuse	5

Reusing treated wastewater has several public perception challenges. Non-potable reuse, has generally been accepted in most parts of the country, although agricultural irrigation must still be handled cautiously. Indirect potable reuse is accepted to a lesser degree, although it is practiced unintentionally. Direct reuse is generally not practiced.

Pollutants of Potential Health Concern

Wastewater effluents may contain a broad spectrum of pollutants of public health concerns, including chemicals and microorganisms. Direct exposure routes for these pollutants include direct contact from contaminated surfaces, accidental ingestion of contaminated water, consumption of raw vegetables irrigated with reclaimed water, and contact of biological aerosols in the vicinity of spray irrigation or cooling towers. Indirectly, wastewater effluent may change the properties of environmental matrices and affect the transport of pollutants in the matrices (e.g., soil irrigated with wastewater effluents) (Khashiboun et al. 2007). Examples of organics of concern are disinfection by-products, pharmaceutically active compounds, N-nitrosodimethylamine (NDMA), 1,4-dioxane, bisphenol A, alkylphenol polyethoxy carboxylates (APECs) and dioxin.

Microorganisms

Pathogens found in domestic wastewater and treated effluents can be classified in three categories: enteric and indigenous bacteria, viruses, and protozoan, as shown in Table 4. These microbial agents have different sizes, health consequences, infective doses, and resistances to environmental stresses and chemical disinfectants. Minimal infective doses of these infectious agents vary widely, ranging from as low as one organism for some viruses and selected protozoa to as high as 10^8 for some bacteria. All these factors are important from the perspective of treating wastewater for reuse.

Table 4: Important Waterborne Pathogens

Bacteria	**Viruses**	**Protozoa**
Campylobacter	Hepatitis A	Giardia
Escheria coli	Reovirus	Cryptosporidium
Salmonella	Calicivirus	Entameoba
Yersinia	Enterovirus	Microsporidium
Vibrio	Coxsackievirus	
Legionella	Adenovirus	
Aeromonas	Echovirus	
Mycobacterium	Poliovirus	
Shigella		
Pseudomonas		

Chemicals

Chemicals with health concerns consist of pesticides, heavy metals, halogenated compounds, and other xenobiotics (Bitton 2005). Some chemical pollutants (e.g., halogenated compounds) are often persistent in the environment and some are often potential carcinogens or can pose acute health effects. In addition to these pollutants, trace levels of pollutants, such as pharmaceutical and personal care products (PPCPs) and endocrine-disrupting chemicals (EDCs), have been found in the final effluents of municipal wastewater treatment plants (Daughton and Ternes 1999; Lishman et al. 2006; Loraine and Pettigrove 2006) and decentralized wastewater treatment systems (Matamoros et al. 2009). EDCs and PPCPs can enter the water through a number of sources including unused drugs disposed through flushing, cleaning and other products poured down the drains or placed in garbage disposals.

Routes of Exposure and Risk Management

Individuals can be exposed both directly and indirectly to reused water. Direct exposure can occur through:

- Contact from surfaces exposed to reclaimed water,
- Accidental ingestion.
- Consumption of fruits and vegetables irrigated with reclaimed water,
- Contact with aerosols from spray irrigation or cooling towers, and/or
- Ingestion through indirect potable reuse

Indirect exposure can occur as a result of the impact on environmental matrices and affect the transport of pollutants (irrigation of soils – overspray)

A multiple barrier approach is employed to reduce the risks to exposure pollutants in reclaimed water. Source control and appropriate treatment with multiple barriers are first employed. These are followed by storage, transmission, and distribution protection through cross connection control/ backflow prevention and pipeline separation. Protection of usage areas is accomplished by warning signs, buffer zones, cross connection control, end-user agreements and user notifications.

Membrane Technology for Minimizing Pollutant Exposure in Wastewater Reuse

Low Pressure Membrane Filtration

Low pressure membrane filtration includes microfiltration (MF) and ultrafiltration (UF) which are typically operated under transmembrane pressures of 2 bars (approximately 30 psi) or less. Commercially available low pressure membranes (LPMs) employed in wastewater reclamation usually have pore sizes ranging between approximately 0.01 μm and 0.1 μm. Since the sizes of bacteria and protozoa (Figure 1) are significantly larger than membrane pore sizes, LPMs are very effective in removing these microorganisms through sieving effects (or mechanical filtration) (Table 5). Due to the relatively small size, the removal of viruses by LPMs, however, varies significantly from none to 5 logs removal for different types of LPMs.

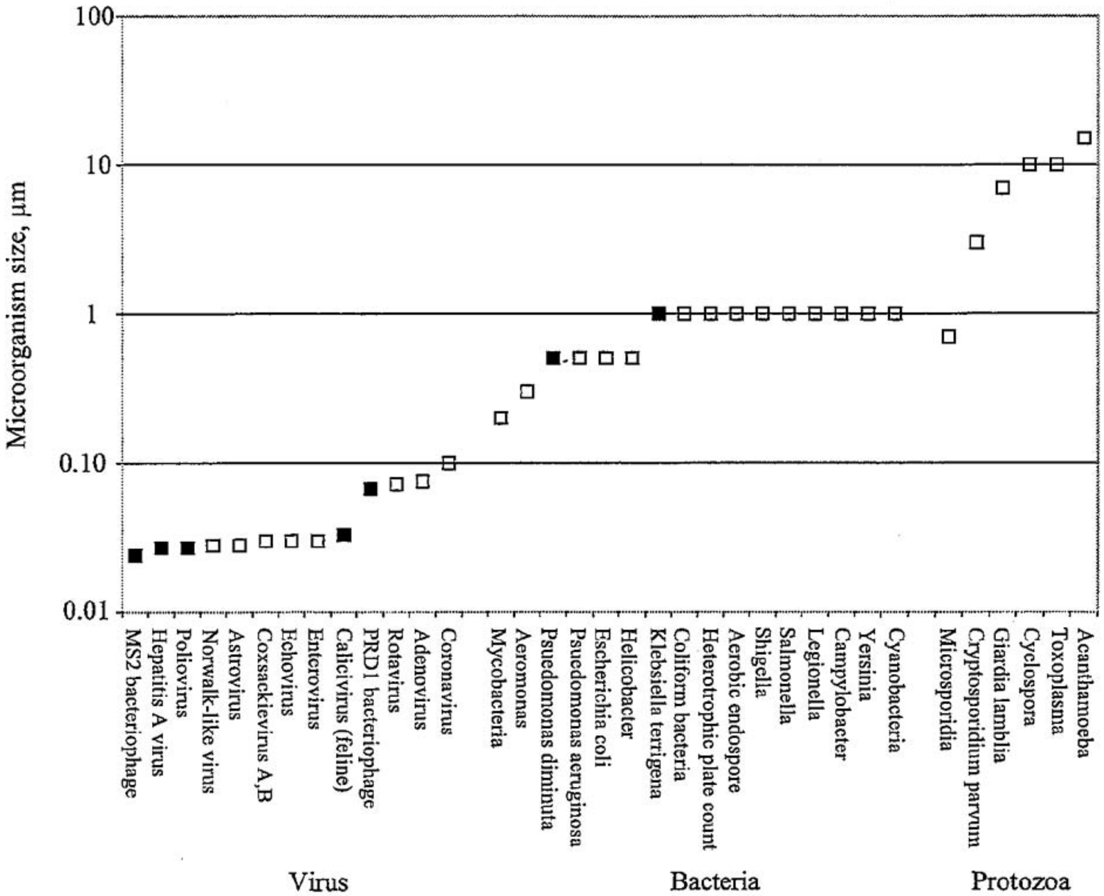

Figure 1: Size of selected microorganisms

Stand-alone LPM filtration facilities are, in general, incapable of removing dissolved pollutants. Therefore, additional treatment processes need to be employed in conjunction with LPM filtration to reduce population exposure to these chemicals. Membrane bioreactors (MBRs), which use integrated biological treatment and LPM filtration, have been increasingly applied in the removal of nutrients and dissolved organic pollutants in wastewater effluents.

<u>High-Pressure Membrane Filtration</u>

High-pressure membrane (HPM) generally refers to reverse osmosis (RO) and nanofiltration (NF). HPMs have smaller more pore sizes and therefore, are more effective in removing dissolved pollutants than LPMs; however, there are usually greater capital and operational costs associated with them Table 5 compares the efficiencies of HPMs (NF and RO) and other optional treatment technologies in the removal of EDCs and PPCPs. As shown in this table, RO is the most effective technology, thereby being preferred for the maximum reduction of population exposure to EDCs and PPCPs in wastewater reuse. An issue with RO is the production of concentrate stream that needs to be treated or disposed properly to avoid secondary pollution or exposure.

Table 5: Comparison of NF/RO and other treatment technologies in removing EDCs and PPCPs. (Shon et al. 2006)

Group	Classification	AC	O_3/AOP	Cl_2/ClO_2	Flocculation	NF	RO
EDC	Pesticides	E	L–E	P–E	P	G	E
	Industrial chemicals	E	F–G	P	P–L	E	E
	Steroids	E	E	E	P	G	E
	Metals	G	P	P	F–G	G	E
	Inorganics	P–L	P	P	P	G	E
	Organometallics	G–E	L–E	P–F	P–L	G–E	E
PPCP	Antibiotics	F–G	L–E	P–G	P–L	E	E
	Antidepressants	G–E	L–E	P–F	P–L	G–E	E
	Anti-inflammatory	E	E	P–F	P	G–E	E
	Sunscreens	G–E	L–E	P–F	P–L	G–E	E
	Antimicrobials	G–E	L–E	P–F	P–L	G–E	E
	Surfactants/detergents	E	F–G	P	P–L	E	E

Note. AC, activated carbon; E, excellent (>90%); G, good (70–90%); F, fair (40–70%); L, low (20–40%); P, poor (<20%). Adapted from Snyder et al. (2003b).

Case Studies

In this section, two case studies using membrane technology for wastewater reuse are discussed to elucidate the effectiveness and key issues to be considered in real-world applications.

San Diego Indirect Potable Water Reuse Project

An advanced water treatment (AWT) system was designed by the City of San Diego, California, to treat the effluent from a wastewater reclamation plant (Figure 2). The treated water from the AWT plant was discharged to San Vicente Reservoir, a potable water source for the city. A key part of this system was the AWT component. A UF-RO-advanced oxidation process (Figure 3) was chosen to treat the tertiary effluent in order to produce quality water and minimize population exposure to pollutants, including PPCPs and EDCs. The designed capacity of the AWT system was 61,000 m^3/day.

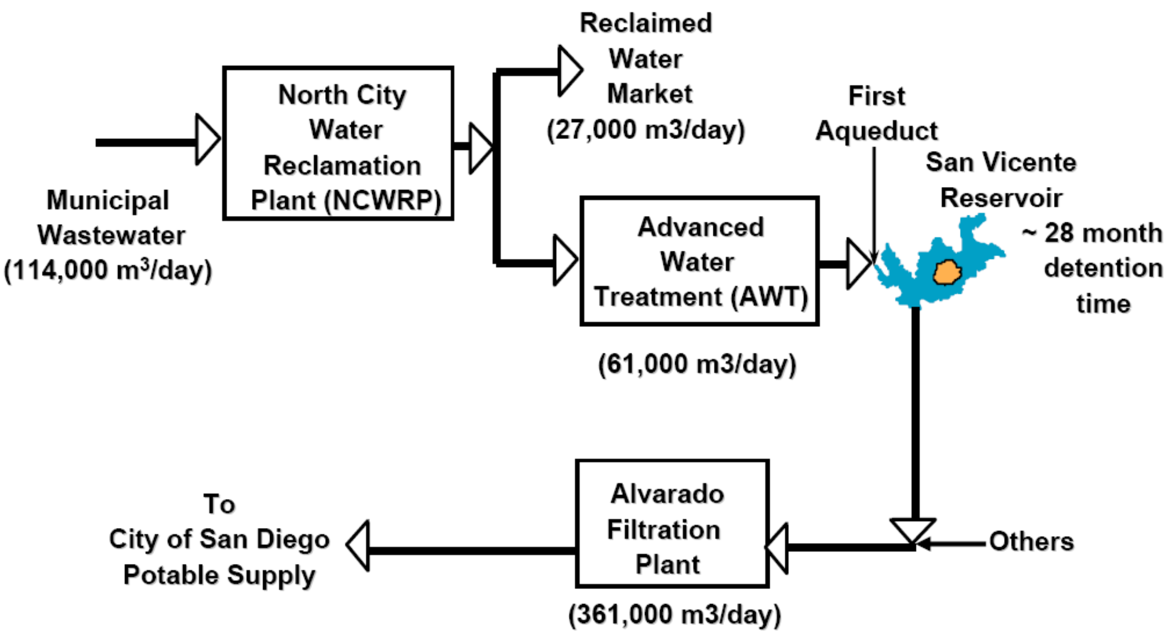

Figure 2: Diagram of wastewater reuse system in City of San Diego, California, USA

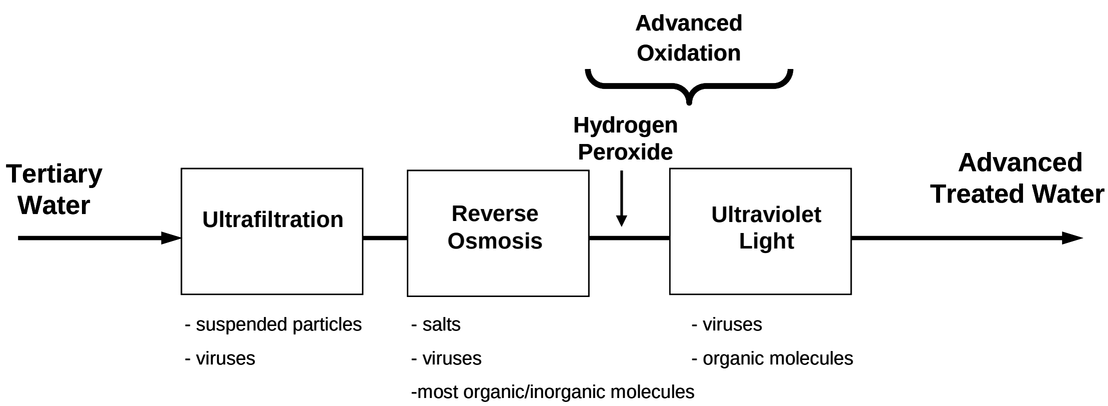

Figure 3: Diagram of the advanced treatment process employed in the San Diego project

A pilot-scale study was conducted to determine the quality of the water produced by the advanced water treatment scheme. Table 6 lists the major operational conditions adopted in this study.

Table 6: Operational conditions employed for the advanced water treatment system.

Ultrafiltration	Target Flux = 51-71 lmh (30-42 gfd)
	Transmembrane Pressure = 6.9 - 69 kPa (1-10 psi)
	Feed Water Recovery ~ 90%
	Ferric Chloride Dose (feed) = 0-2.5 mg/L
	Free Chlorine Dose (feed) = 0 - 2 mg/L
	Free Chlorine Dose during backwash = 10 mg/L
Reverse Osmosis	Flux = 20 lmh (12 gfd)
	Feed Water Recovery = 75-85%
	Feed pH = 7 - 8
	Antiscalant Dose = 2 mg/L
	Combined Chlorine Dose (feed) = 1-2 mg/L
UV	Target Flow = 378.5 L/h (100 gpm)
	Lamp Power ~ 1200 W
	Power Setting = 60 %
	Hydrogen Peroxide Dose = 5 mg/L

The product water of the AWT system was characterized for all compounds regulated for drinking water as well as other concerned contaminants, including 29 EDC and PPCP compounds. The results showed that all compounds regulated in drinking water were below their MCLs, 21 contaminants of concern were below their notification levels, and 29 EDC/PPCP were below their method detection limits. Therefore, RO was effective at removing all compounds regulated in drinking water and selected EDC/PPCPs. These findings were consistent with similar published studies obtained in Water Factory 21, Orange County, California and West Basin Water Recycling Plant - El Segundo, California.

Table 7 presents the concentrations of selected PPCPs and EDCs measured in the influent and effluent of the RO system, as well as the effluent of the UV/peroxide treatment. The results showed that RO removed all the compounds to close or below the method detection limits, while UV/peroxide only provided minor improvement for the removals of trimethoprim, sulfamethoxazole, and several other compounds. The quality of the water produced by the AWT process was similar to that of the receiving lake and below the MCL or notification levels when TTHMs, chloroform, nitrate, dioxane, and NDMA were compared, as shown in Table 8.

Table 7: Removal of selected PPCPs and EDCs by the advanced water treatment process

Parameter	Units	Method Detection Limit	AWT Process Location		
			RO In (n=2)	RO Out (n=2)	UV + Peroxide (n=2)
Hydrocodone	ng/L	1	80	<1.0	<1.0
Trimethoprim	ng/L	1	384	2.95	<1.0
Acetaminophen	ng/L	10	<10	<10	<10
Caffeine	ng/L	10	<10	<10	<10
Erythromycin-H2O	ng/L	1	298	<1.0	<1.0
Sulfamethoxazole	ng/L	1	892	2.9	<1.0
Fluoxetine	ng/L	1	33	<1.0	<1.0
Pentoxifylline	ng/L	1	12	<1.0	<1.0
Meprobamate	ng/L	1	292	1.5	<1.0
Dilantin	ng/L	1	144	<1.0	<1.0
TCEP	ng/L	10	272	<10	<10
Carbamazepine	ng/L	1	279	2.4	<1.0
DEET	ng/L	5	293	<5.0	<5.0
Atrazine	ng/L	1	1	<1.0	<1.0
Diazepam	ng/L	1	1	<1.0	<1.0
Oxybenzone	ng/L	5	21	<5.0	<5.0
Estriol	ng/L	5	14	<5.0	<5.0
Ethynylestradiol	ng/L	1	<1.0	<1.0	<1.0
Estrone	ng/L	1	101	<1.0	<1.0
Estradiol	ng/L	1	18	<1.0	<1.0
Testosterone	ng/L	1	<1.0	<1.0	<1.0
Progesterone	ng/L	1	<1.0	<1.0	<1.0
Androstenedione	ng/L	1	5	<1.0	<1.0
Iopromide	ng/L	1	632	1.4	<1.0
Naproxen	ng/L	1	255	1.2	<1.0
Ibuprofen	ng/L	1	79	<1.0	<1.0
Diclofenac	ng/L	1	89	<1.0	<1.0
Triclosan	ng/L	1	[1] 324	[1] 3.4	[1] <1.0
Gemfibrozil	ng/L	1	1022	1.3	<1.0

[1] n = 1

Table 8: Concentrations of pollutants in AWT effluent and receiving water bodies

Compound(s)	Units	AWT Product	Lake 1	Lake 2	MCL or Notification Limit
TTHMs	mg/L	0.003	0.003	ND	0.08
Chloroform	mg/L	0.023	0.0012	ND	--------
Nitrate as N	mg/L	1.6	ND	0.64	10
1,4 Dioxane	mg/L	0.0028	ND	ND	0.003
NDMA	mg/L	0.0000023	ND	ND	0.00001

Sunrise, Florida MBR Project

The objectives of this project were to investigate the potential of using MBR and appropriate post-treatment to treat raw sewage to meet the national and local standards/guidelines for groundwater recharge. Figure 4 shows the process. Table 9 summarizes the values for major pollutants.

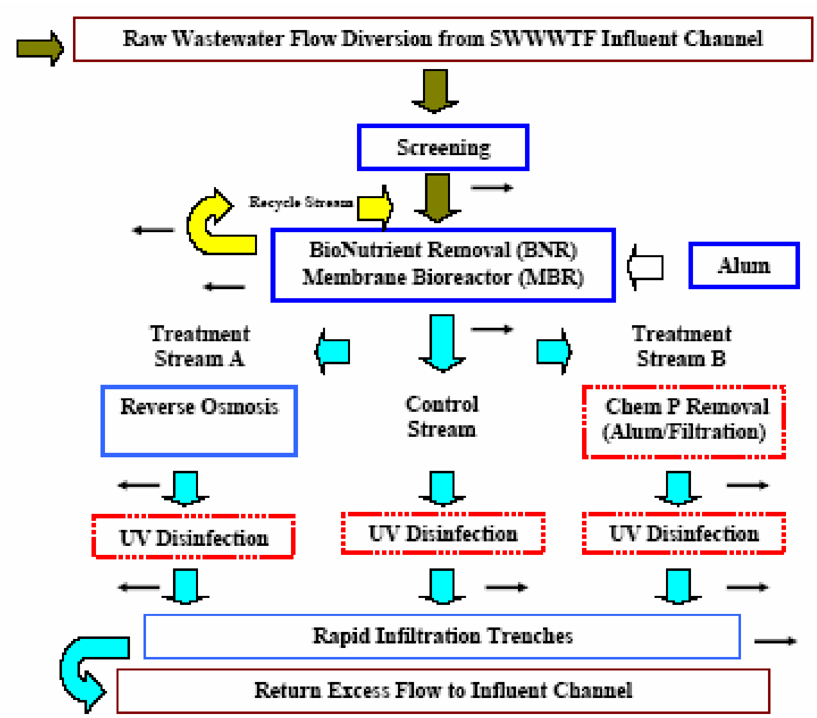

Figure 4: Diagram of the wastewater reuse process for the City of Sun Rise, Florida, USA

Table 9: Water quality standards/guidelines for groundwater recharge.

Compound/Parameter	Broward County Std	Florida State Standard	National Water Standard
$CBOD_5$	5 mg/l	20 mg/l	5 mg/l
Total Suspended Solids (TSS)	-	5 mg/l	5 mg/l
Chlorine (Total Residual)	1 mg/l	-	1 mg/l
Total Nitrogen (TN)	no.	-	10 mg/l
Nitrate (as N)	10 mg/l	10 mg/l	10 mg/l
Nitrite (as N)	1 mg/l	1 mg/l	1 mg/l
Total Nitrate + Nitrite	10 mg/l	10 mg/l	10 mg/l
Total Phosphates (as P)	0.01 mg/l	-	0.01 mg/l
Fecal Coliform	200 / 100 ml	-	200 / 100 ml
Total Coliform	1,000 / 100 ml	-	1,000 / 100 ml
Total Dissolved Solids (TDS)	500 mg/l	500 mg/l	500 mg/l
Turbidity	10 NTUs	-	10 NTUs

A critical requirement for the treatment was to ensure that the concentration of phosphorus in the product water was below 0.01 mg P/L as mandated by Broward County, Florida, (Table 9); this was a challenge considering an average phosphate concentration of 8 mg P/L in the raw sewage (Table 10). Three treatment trains were tested at pilot scale: MBR-UV-rapid infiltration, MBR-RO-UV-rapid infiltration, and MBR-alum coagulation-UV-rapid infiltration.

Table 10: Characteristics of the raw sewage treated by the MBR

Compound	Units	Range	Average
Biological Oxygen Demand (CBOD5)	mg/L	90 – 480	244
Total Suspended Solids (TSS)	mg/L	26 –240	130
Total Nitrogen (TN)	mg/L	7 – 78	40
Total Phosphorus (TP)	mg/L	8 – 33	22
Total Phosphates	mg/L	1 – 11	8

As shown in Figure 5, when the phosphate concentration in the influent was between 3 mg/L and 8 mg/L, phosphate concentration in the MBR effluent varied in a broad range of approximately 0.008 mg/L to 1.0 mg/L; after RO treatment, phosphate concentration was consistently below 0.01 mg/L, which met the aforementioned guideline for phosphate in treated water for groundwater recharge.

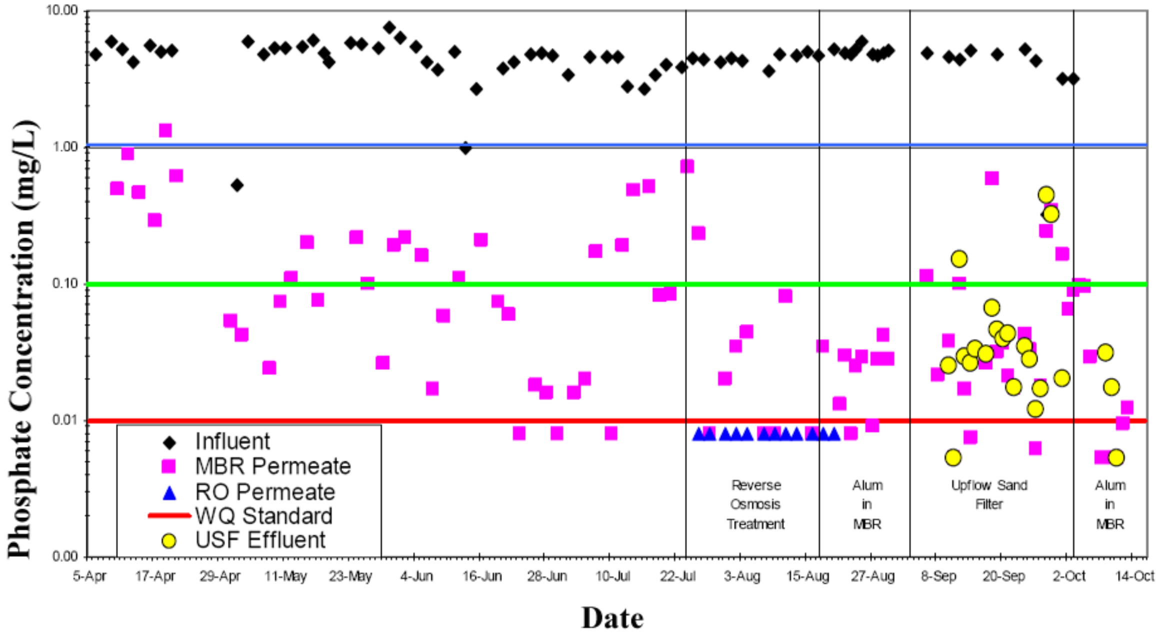

Figure 5: Removals of phosphate at different steps of the treatment process during the pilot-scale study.

After the MBR treatment, $CBOD_5$, nitrogen, and suspended solids in the wastewater were also removed to levels below the requirements of related water quality standards/guidelines. The removals of micropollutants by the MBR or MBR-RO process were promising. As shown in Figure 6, caffeine and acetaminophen were removed to below 1 ng/L with MBR treatment. In comparison, MBR removed less than 50 percent of ibuprofen and n-nitroso dimethylamine (NDMA), and downstream treatment with RO was needed to effectively remove the residual pollutants.

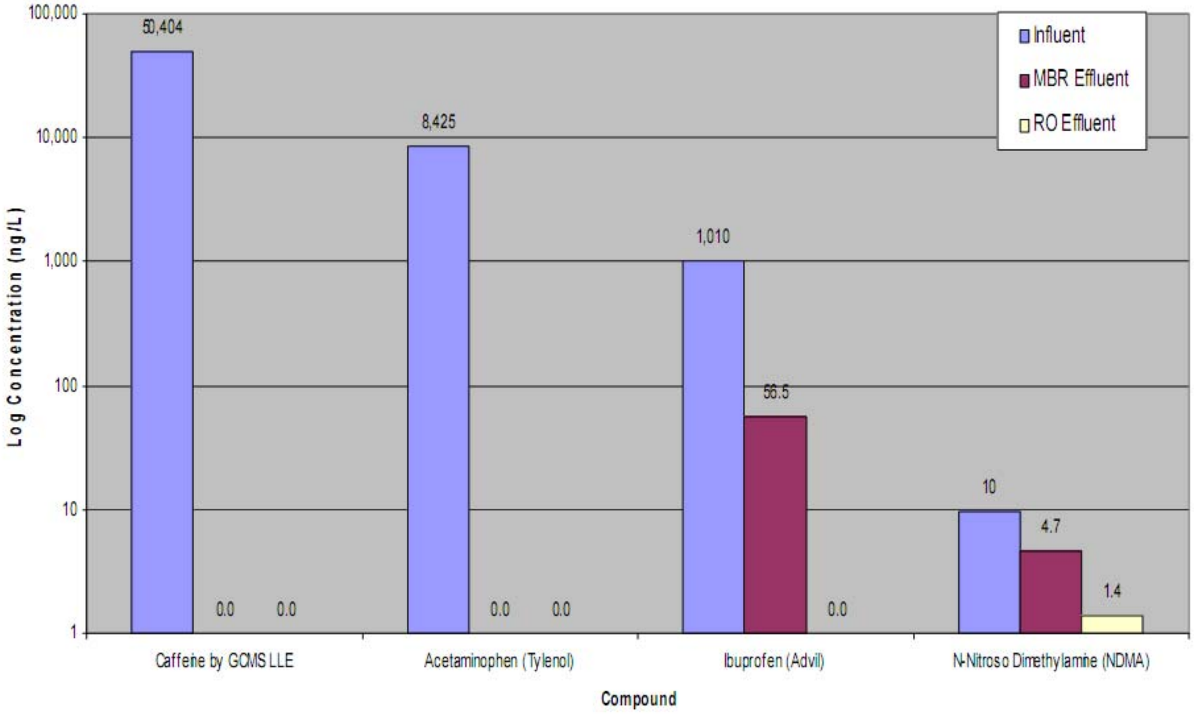

Figure 6: Removals of selected PPCPs/EDCs by MBR and MBR-RO treatment obtained in the Sunrise, Florida pilot study.

Trends in Water Reuse

Moving forward, there are a number of trends in treatment for water reuse that are popular, including:

- Dual systems
- Indirect potable reuse with ID change
- UV for disinfection and advanced oxidation
- Membrane processes
- Distributed water reuse facilities

Federal and state agencies are continuing to develop regulations. Agencies, water treatment facilities and industry will continue to integrate their resources. User perception studies will continue. Water reuse will also continue to be a center for sustainable development, for example in the United Arab Emirates.

Conclusion

Wastewater reuse has been increasingly employed around the world to overcome the shortage of water resources. The presence of pathogens and chemicals in wastewater poses potential risks of human exposure during potable or non-potable water reuse processes, which may undermine the benefits obtained with more efficient utilization of water resources. Pathogens and a variety of trace-concentration pollutants (micropollutants) have drawn the most attentions due to their impacts in this regard. Therefore, efficient and reliable treatment processes are necessary to reduce population exposure during wastewater reuse.

Application of membrane technology to water treatment provides a potential solution to this issue. Membrane technology employed in water treatment comprises LPM filtration (MF and UF) and HPM filtration (NF and RO) if classified by operational pressure. LPM filtration is effective in removing pathogens and particles; some dissolved pollutants may also be removed if integrated with other treatment processes, including biological treatment. In comparison, HPM filtration is capable of directly removing dissolved pollutants of health concerns, such as PPCPs and EDCs.

Two case studies were discussed here to elucidate the application of different membrane processes (UF, RO, MBR and their combinations) to produce high-quality reclaimed waters for indirect potable reuse. As found in the pilot-scale studies, the treated water met the quality standards/guidelines for discharge to receiving water bodies or groundwater recharge. These findings provide important evidence to the efficiency of membrane systems for indirect potable water reuse. The reliability/sustainability of membrane technology needs to be determined in long-term studies. Future research on the applicability of membrane technology to other types of wastewater reuse is also warranted.

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