Potable Reuse Treatment Trains throughout the World

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ABSTRACT

Potable reuse is becoming an increasingly common strategy for bolstering water resource portfolios in water-scarce regions. Each application poses unique challenges, whether related to treatment goals, regulatory requirements, or political and public acceptance, and these issues have a significant impact on the final treatment train selection. This review describes the various potable reuse frameworks and illustrates the importance of environmental buffers as a treatment barrier and as a distinction between 'indirect' and 'direct' potable reuse applications. This review also highlights more than 20 potable reuse treatment trains currently in operation or under construction throughout the world. The unit processes in each train are identified and a brief summary of their advantages and limitations in relation to alternative processes is included.

Key words | advanced water treatment, potable reuse, treatment train, water reuse

List of abbreviations

AOP	Advanced oxidation process
BAC	Biological activated carbon
BACT	Best available control technology
BOD	Biochemical oxygen demand
CDPH	California Department of Public Health
CEC	Contaminant of emerging concern
COD	Chemical oxygen demand
DOC	Dissolved organic carbon
DPR	Direct potable reuse
EBCT	Empty bed contact time
EPA	Environmental Protection Agency
FAT	Full advanced treatment
GAC	Granular activated carbon
MF	Microfiltration
NDMA	N-nitrosodimethylamine
NF	Nanofiltration
NL	Notification level
NRC	National Research Council
O&M	Operations and maintenance

PAC	Powdered activated carbon
RO	Reverse osmosis
RWC	Recycled water contribution
SRT	Solids retention time
TOC	Total organic carbon
TOrC	Trace organic contaminant
TSS	Total suspended solids
UF	Ultrafiltration
U.S.	United States
UV	Ultraviolet
WHO	World Health Organization

INTRODUCTION

Rapid population growth often occurs in areas with increasingly stressed water supplies resulting from arid conditions, climate change, and natural variability (U.S. Department of the Interior 2003; Asano *et al.* 2007). As a result, there is an increasing global trend toward more efficient use of water resources in both urban and rural communities. In addition to innovative water management and acquisition strategies, such as water transfers, banking, and trading, municipalities are turning to water reuse in a variety of contexts to bolster their water portfolios. The benefits of water reuse are generally more pronounced in arid and semi-arid regions, but these benefits can also be experienced by coastal communities faced with saltwater intrusion or any region where the quantity or quality of the water supply may be compromised.

Reuse systems, particularly in potable applications, include a multi-barrier treatment framework composed of advanced unit processes, and they often incorporate resiliency (i.e., ability to adjust to upsets), redundancy (i.e., backup systems), and robustness (i.e., features that simultaneously address multiple contaminants) (National Research Council [NRC] 2012). In comparison to conventional source waters, potable reuse is often scrutinized more carefully by the water industry, held to higher water quality standards by water regulators, and tested for a wider range of chemical and microbial contaminants. Despite an inevitably higher level of initial contamination, these systems may provide a greater level of public health protection than many common water sources treated with conventional drinking water processes, as illustrated by the 'risk exemplar' developed by the United States (U.S.) National Research Council (NRC 2012).

Each reuse application poses unique challenges related to financial constraints, treatment objectives, regulatory permitting, and public acceptance. Water reuse treatment trains may be dictated by one or more variables (e.g., regulations) in some instances, while other applications may allow for a wide variety of treatment options. This is reflected in the diversity of potable reuse treatment trains throughout the world, many of which have been operating successfully for years or even decades. This diversity may be attributed to the site-specific challenges described above or simply the time period in which the project was implemented. Certain treatment technologies have experienced cycles of popularity over the past few decades (e.g., ozone) (Oneby *et al*. 2010; Gerrity & Snyder 2011), and other technologies have become more technologically or economically feasible (e.g., reverse osmosis (RO)) in recent years. Attention has also shifted to new classes and groups of contaminants as analytical methods have improved (Vanderford & Snyder 2006) and bioassays have become more useful and reliable (Macova *et al.* 2010). Some of these contaminants of emerging concern (CECs) are better addressed by specific technologies or the synergism between multiple technologies. Although conservatism is critical to the safety of potable reuse, the recent emphasis on CECs may be leading to the overdesign of treatment facilities, which reduces their cost effectiveness. This is illustrated by the high 'margins of exposure' or 'margins of safety' linked to potable reuse treatment trains in recent toxicological assessments (Bull *et al*. 2011; NRC 2012).

In general, there is a lack of regulatory guidance related to potable reuse, and the urgent need for new water supplies often outpaces traditional planning and public discourse on the topic. For example, the Western Corridor Recycled Water Project in Australia involved a nearly $\$2\text{x}10^9$ (U.S.) investment to rapidly construct three advanced treatment plants in the midst of an intense drought (Freeman *et al.* 2008). Due to a lack of political and public support, the facilities were only used for industrial applications, and more recently, there has been discussion of shutting the project down entirely due to a reprieve in drought conditions coupled with the facilities' high operational costs. Similar situations are unfolding in Texas where water agencies are urgently developing direct potable reuse systems to help municipalities cope with water shortages.

The intent of this paper is to aid such agencies by providing a 'toolbox' that summarizes potable reuse systems throughout the world and identifies the advantages and limitations of the major potable reuse paradigms. In addition, this paper increases familiarity with the concept of potable reuse, which is critical to improving public perception and garnering support for such projects (Marks 2006; Marks *et al*. 2006; Rock *et al.* 2012).

INDIRECT POTABLE REUSE (IPR)

For several decades, most reuse projects were limited to non-potable applications, such as municipal and agricultural irrigation and industrial reuse, but diminishing water supplies, dramatic population growth, historic drought conditions, the high cost of parallel infrastructure, and a greater acceptance and understanding of reuse have led to more potable applications as well. In recent years, the most notable application has been 'indirect' potable reuse (IPR) through the augmentation of a community's raw water supply with treated wastewater followed by an environmental buffer (Environmental Protection Agency [EPA] 2012), as illustrated by pathway B in Figure 1. Prior to adopting this formal definition, many drinking water treatment plants had been withdrawing their water supply downstream of wastewater discharges. Recognizing that such projects were engaging in reuse despite the fact that they were not officially recognized nor permitted as reuse projects, the NRC (2012) adopted the term *de facto* reuse – a term originally proposed by Asano *et al*. (2007). The concept of *de facto* reuse is illustrated by pathway A in Figure 1.

Despite these seemingly straightforward definitions, there are countless variations of IPR and *de facto* reuse throughout the U.S. and the world. The concept of *de facto* reuse often involves substantial dilution factors when treated wastewater effluent is discharged into large surface waters, but there are also scenarios where the treated wastewater effluent may constitute a majority or even the entirety of a water body, particularly during periods of drought in semi-arid environments (NRC 2012). In dedicated or ‘planned’ IPR systems, treatment ranges from conventional wastewater treatment, which includes the headworks, primary clarification, and a secondary biological process, to ‘full advanced treatment’ (FAT), a term introduced by the California Department of Public Health (CDPH) that encompasses microfiltration (MF), RO, and an advanced oxidation process (AOP) (CDPH 2013). Although FAT is often considered the standard treatment train for potable reuse, its widespread implementation is hindered by a number of sustainability issues, including high capital and operations and maintenance (O&M) costs, high energy consumption, practical limits on water recovery, and the need to discharge concentrated brine streams. As a result, a number of ozone-based alternatives are increasing in popularity throughout the world.

THE CASE FOR DIRECT POTABLE REUSE (DPR)

All *de facto* reuse and IPR systems share at least one critical trait: environmental buffers via groundwater replenishment or surface water discharge. Recent discussions among water reuse experts have questioned whether these environmental buffers are actually necessary or whether it is more appropriate to transition to engineered storage buffers in some situations (Leverenz *et al.* 2011). In such ‘direct’ potable reuse (DPR) applications, the product of a conventional or advanced wastewater treatment train is either discharged into a raw water source immediately upstream of a drinking water treatment plant, blended with the product water from a drinking water treatment plant, or immediately introduced into a potable distribution system. These emerging paradigms are illustrated in pathway C in Figure 1.

DPR is a controversial topic, but there are a number of attributes that warrant its implementation over non-potable reuse, IPR, and conventional source waters. The development of non-potable reuse applications, while requiring less treatment than IPR or DPR, requires a substantial investment in urban infrastructure in the form of dual distribution systems for non-potable and potable supplies (Leverenz *et al*. 2011; NRC 2012). Tertiary recycled water used for irrigation may cost up to \$1.70/m^3, while potable reuse ranges from \$0.60-\$1.00/m^3 (Leverenz *et al*. 2011). For IPR systems, the transport of the finished product to the environmental buffer may also involve significant costs and energy consumption. In Las Vegas, for example, treated wastewater effluent flows by gravity to Lake Mead, but the water must then be pumped over mountains before being treated and returned to the consumer as a potable supply. In San Diego's proposed IPR system, FAT product water will be pumped more than 20 miles, discharged into the San Vicente Reservoir, and then allowed to flow back into the metropolitan area. In some conventional water systems, including Arizona and California, source water is pumped hundreds of miles to meet the demands of burgeoning urban areas. After accounting for the life cycle costs and energy consumption of imported water supplies, IPR, or desalination, the advanced treatment trains required for DPR may be a more cost and energy efficient alternative (Leverenz *et al*. 2011).

Despite the costs, environmental buffers in IPR systems provide several benefits that would be lost or reduced in the transition to DPR. For example, they allow for the storage of recycled water when excess is available (i.e., in the fall and winter) and consumption of recycled water when there is excess demand (i.e., in the spring and summer). Environmental buffers also provide ample time to identify and respond to operational breakdowns prior to distribution of a potentially contaminated water source. However, engineered storage buffers in DPR systems could be designed to satisfy a specified response or buffer time (Leverenz *et al*. 2011; Tchobanoglous *et al.* 2011). The NRC reported that the need for storage between the point of production and the point of use will actually diminish as technologies for attenuation and monitoring continue to improve (NRC 2012). However, it is unlikely that engineered storage buffers could provide the same long-term storage capacity provided by most IPR systems due to practical size limitations.

In IPR applications, reintroduction of the purified water into the environment allows the public to reframe its understanding of the water, thereby eliminating the mental association with its wastewater origin. While environmental buffers provide a valuable treatment barrier when used in conjunction with some treatment trains (e.g., tertiary filtration, disinfection, and soil aquifer treatment (SAT)), this is not necessarily true in all applications. With environmental discharge, there is always a possibility for water quality degradation due to agricultural, industrial, municipal, or even natural contaminants (Leverenz *et al.* 2011). In some scenarios, the spreading of FAT product water—essentially RO permeate—may lead to significant leaching of organic carbon or toxic metals, such as arsenic, from the soil (Drewes *et al*. 2010). After considering each of these elements, DPR has the potential for higher water recovery, a higher quality product, and lower treatment costs since the water is of local origin and can theoretically be treated at a single facility with a single collection and distribution system (Leverenz *et al*. 2011; NRC 2012).

POTABLE REUSE TREATMENT TRAINS

With the exception of the system in Windhoek, Namibia (described later), the concept of DPR is relatively novel so the suitability of existing IPR treatment trains for DPR applications is currently being debated. In this emerging paradigm, the principal question is whether existing treatment trains should include additional unit processes to replace the treatment and time benefits provided by environmental buffers. To this end, the NRC (2012) proposed to eliminate the distinction between indirect and direct applications and focus on potable reuse as a single concept. Within this framework, potable reuse treatment trains must simply demonstrate specified levels of chemical and microbial contaminant removal (based on initial loadings in the raw sewage or secondary effluent) and satisfy established drinking water regulations (e.g., U.S. Environmental Protection Agency (EPA) Primary Drinking Water Standards). Treatment trains are assembled accordingly, and environmental buffers, if applicable, are treated as unit processes. When environmental buffers are included, regulatory compliance is often demonstrated without consideration of any downstream drinking water treatment processes. Therefore, the descriptions provided below generally exclude the associated drinking water treatment facilities and focus on the conventional and advanced wastewater treatment trains in benchmark potable reuse systems throughout the world.

Wastewater treatment plant service area and catchment

The first step in determining the efficacy and expected water quality of a potable reuse treatment train involves the characterization of the service or catchment area for the wastewater treatment plant (Dominguez-Chicas & Scrimshaw 2010). This includes estimates of the average daily flow and diurnal variations in addition to the relative contributions of municipal, industrial, and agricultural sources. The general quality of domestic wastewater may be predicted under normal flow conditions, but there are still significant variations for some contaminants as use patterns and loadings shift throughout the day, between weekdays and weekends, and between seasons. Recent studies have shown that the concentrations of some trace organic contaminants (TOrCs) can exhibit considerable temporal variability in domestic wastewater (Joss *et al*. 2005; Takao *et al*. 2008; Plosz *et al*. 2010; Gerrity *et al*. 2011b; Nelson *et al.* 2011; Postigo *et al*. 2011)—even on time scales as short as one minute (Ort *et al*. 2010).

Intermittent contributions from agricultural runoff, livestock runoff, or slaughterhouses may also cause spikes in nutrients, parasites (e.g., *Cryptosporidium*), and veterinary pharmaceuticals (Sim *et al*. 2011). Furthermore, hospital discharges may contribute more concentrated and diverse mixtures of pharmaceuticals (Sim *et al.* 2010), and industrial discharges may contain organic compounds and other materials that are typically absent in domestic wastewater. The levels of enteric pathogens—the primary acute risk associated with potable reuse—may also vary during the day and throughout the season, depending on the level of enteric disease in the community. Therefore, it is important to account for all potential wastewater sources and consider the associated flows as discrete packets of chemical and microbial contaminants with potential temporal variability (Ort *et al*. 2010). Once the wastewater sources and anticipated contaminant loads have been characterized, it is possible to determine the total removal required for various contaminants, identify appropriate treatment trains, and ultimately satisfy public health criteria.

***De facto* reuse with conventional wastewater treatment**

De facto reuse involves the discharge of treated wastewater from an upstream community into the source water of downstream communities. In these scenarios, the downstream communities have little control over the quality of water received at their intakes. In the U.S., National Pollutant Discharge Elimination System (NPDES) permits, which are mandated by the U.S. EPA Clean Water Act (CWA), necessitate some degree of contaminant mitigation primarily to ensure the environmental waters are fishable and swimmable. Making the water suitable as a drinking water source is not the primary goal, although protection of this beneficial use is enabled under the CWA legislation and has been implemented in some jurisdictions (NRC 2012).

In the U.S., the Mississippi River, the Trinity River in Texas, and the Schuylkill River in Pennsylvania are examples of *de facto* reuse. The Mississippi River receives wastewater discharges from 10 different states at various locations along the river, and many of those states also designate the river as a domestic water supply. In 2006, there were 803 total NPDES permits for sewerage (257) and industrial (546) discharges into the Mississippi River (NRC 2008). Although these dischargers are required to meet certain water quality objectives based on their NPDES permits, the NPDES primarily targets ‘conventional pollutants’, such as biochemical oxygen demand (BOD), total suspended solids (TSS), fecal coliforms, oil and grease, pH, and a list of 126 ‘priority pollutants’ established in 1977. These requirements largely ignore TOrCs, which have received increased attention in recent years (NRC 2012). Due to the tremendous flows of the Mississippi River, the wastewater discharges are often highly diluted, but this is not necessarily the case in all *de facto* reuse systems. The Trinity River, which is a major source water for the Houston Metropolitan Area, is almost entirely wastewater effluent under base-flow conditions (NRC 2012). After two weeks of travel time and wetlands treatment, the river eventually empties into Lake Livingston where it is stored for an additional year prior to withdrawal by drinking water treatment plants in Houston.

There are numerous examples of *de facto* reuse throughout the world, and each system offers unique challenges for downstream communities due to the range of treatment processes and operational conditions employed at the upstream facilities. The aforementioned effluent discharge requirements are often based on best available control technologies (BACTs), but compliance can generally be achieved with preliminary treatment (i.e., bar screens), primary treatment (i.e., primary clarifiers), and secondary treatment (i.e., biological treatment and secondary clarifiers). The secondary biological process in a conventional wastewater treatment plant generally consists of trickling filters, rotating biological contactors, aerated lagoons, or conventional activated sludge processes. Some systems have implemented tertiary treatment and/or final disinfection with chlorine, chloramine, ozone, UV, or other disinfectants, but there are also facilities that discharge immediately after secondary treatment (Figure 2A). As a result, there is potential for adverse human health impacts unless downstream drinking water treatment facilities are designed with robust, multi-barrier treatment trains.

Potable reuse with conventional wastewater treatment and surface water discharge

'Planned' potable reuse involves the intended discharge of treated wastewater from one community into its own source water in an effort to augment its water resource portfolio. In such systems, water and wastewater treatment agencies have the opportunity to collaborate to improve the quality of the wastewater effluent, source water, and finished drinking water in an effort to protect public health. The wastewater treatment trains may be similar to those of *de facto* reuse, although there are countless modifications that have been implemented to improve the quality of the final effluent. With respect to conventional wastewater treatment, many of these modifications relate to the secondary biological process, including increased solids retention times (SRTs) and the addition of microbial selectors to achieve nitrification, denitrification, and/or biological phosphorus removal. Chemical addition to improve particle settling or phosphorus removal is also common. These treatment trains generally include some form of tertiary treatment (i.e., filtration with granular media or membranes) and final disinfection with chlorine, chloramine, germicidal UV light, or ozone, as illustrated in Figure 2B.

Tertiary wastewater treatment supplemented with final disinfection can be effective in reducing the concentrations of many TOrCs and microbial pathogens. However, the level of reduction varies considerably depending on the contaminant of interest (e.g., bacteria, viruses, or parasites; naproxen, carbamazepine, or meprobamate), the SRT in the secondary biological treatment process (Gerrity *et al.* 2013), and the final disinfection process. Chloramines are moderately effective for the inactivation of bacterial pathogens, and free chlorine is effective for both bacterial and viral pathogens (Crittenden *et al.* 2005). However, ozone and UV disinfection have been identified as more robust disinfection alternatives when targeting parasites as well, although ozone even has limited efficacy against *Cryptosporidium* (Crittenden *et al.* 2005). Ozone is also effective for TOrC mitigation, while the other disinfectants have limited efficacy (Westerhoff *et al*. 2005; Snyder *et al.* 2013). After final disinfection, the finished effluent is discharged to the environment, which provides further contaminant attenuation through a variety of physical (e.g., adsorption and solar photolysis) and biodegradation pathways.

The Las Vegas Metropolitan Area is an example of potable reuse with conventional wastewater treatment optimized for nutrient control. The $2.3x10^5$ m^3/d City of Las Vegas Water Pollution Control Facility, the $3.8x10^5$ m^3/d Central Plant of the Clark County Water Reclamation District, and the $1.5x10^5$ m^3/d Kurt R. Segler Water Reclamation Facility in the City of Henderson service most of the metropolitan area, and they discharge a large percentage of their treated effluent to the Las Vegas Wash, which eventually feeds into Lake Mead. These facilities target varying levels of nitrification, denitrification, and phosphorus removal to reduce the likelihood of algal blooms in Lake Mead, and they also employ granular media filtration and final disinfection with chlorine or UV. The Clark County Water Reclamation District, which is the major contributor to the flows in the Las Vegas Wash, will soon be employing ultrafiltration (UF) and ozone to further reduce phosphorus discharges, improve disinfection, and reduce estrogenicity and TOrC concentrations in the final effluent.

Prior to these agencies implementing a stringent phosphorus removal plan, Lake Mead was affected by a significant algal bloom in 2001 during which chlorophyll A concentrations exceeded 1,000 mg/m^3 (Nevada Division of Environmental Protection [NDEP] 2001). For context, concentrations exceeding 40 mg/m^3 are indicative of highly eutrophic conditions (NDEP 2001). The bloom was attributed to a ‘perfect storm’ of events, including low reservoir levels, high rainfall and subsequent runoff, and wastewater-related nutrient loadings (NDEP 2001). Most of the problems resulting from this bloom were related to recreation and the aesthetic quality of the reservoir. Although there can be potential public health concerns due to cyanotoxins associated with certain types of algae (Carmichael *et al*. 2001), there were no public health impacts associated with this particular bloom.

Prior to the algal bloom, the Las Vegas Metropolitan Area was also affected by an outbreak of cryptosporidiosis in 1994 during which more than 100 people were infected and approximately 20 deaths were reported (EPA 2001). Although the source of the outbreak was never definitively identified, evidence suggests that the exposure may have occurred through drinking water consumption, and some people attribute the contamination to the upstream wastewater effluent discharge in Las Vegas Bay (Goldstein *et al*. 1996). As a result, the drinking water facilities in the Las Vegas Metropolitan Area were equipped with ozonation to provide an additional barrier against *Cryptosporidium* oocysts. Coincidentally, the outbreak of cryptosporidiosis in Milwaukee in 1993, which led to more than 403,000 infections and 100 deaths, occurred under similar conditions (MacKenzie *et al*. 1994). The source of the outbreak was never confirmed, but an upstream wastewater discharge was suspected of contaminating the drinking water intake during an extreme runoff event that resulted in sewer overflows. Similar to Las Vegas, the Milwaukee drinking water treatment facilities were subsequently equipped with ozonation, and the South Milwaukee Wastewater Treatment Plant was equipped with UV disinfection to reduce the likelihood of future outbreaks.

Although these two outbreaks indicate the potential for adverse human health effects, they are isolated cases over decades of potable reuse, and it is important to reiterate that the outbreaks were never definitively linked to the wastewater discharges. In response to the outbreaks of cryptosporidiosis, the wastewater and drinking water treatment trains in both Las Vegas and Milwaukee were upgraded with more robust forms of disinfection (i.e., UV in wastewater and ozone in drinking water), and the risk of future waterborne disease outbreaks was clearly reduced. Therefore, potable reuse systems that are specifically designed to address excess pathogen loads may actually have lower health risks than some conventional source waters (NRC 2012)

Potable reuse with conventional wastewater treatment and soil aquifer treatment

Particularly in California, the use of conventional wastewater treatment followed by groundwater replenishment (Figure 2B) has been a successful potable reuse model for decades. This approach relies on the efficacy of SAT to ensure that the final product water is safe for human consumption. A prime example of SAT is the Montebello Forebay Groundwater Recharge Project in California. This system, which involves the spreading of disinfected tertiary effluent, is operated by the Sanitation Districts of Los Angeles County and the Water Replenishment District of Southern California and has been in operation since 1962. Long-term epidemiological studies were conducted to evaluate the safety of this system, and they identified no significant health impacts, such as adverse birth outcomes, cancer rates, mortality, and infectious disease, after nearly four decades of water consumption (Sloss *et al.* 1996; NRC 1998; Sloss *et al.* 1999). A similar groundwater recharge system managed by the Inland Empire Utilities Agency in California combines stormwater, imported water, and recycled water and has been in operation since 2005.

Particularly in the case of California reuse regulations, SAT is a critical factor in achieving log removal requirements for pathogens. CDPH requires 12-10-10-log removal for viruses, *Cryptosporidium*, and *Giardia*, respectively. Conventional wastewater treatment, filtration, and disinfection account for at least 6 logs of virus credit. Agencies are then awarded an additional 1 log of virus credit for each month that the water is retained underground. The *Cryptosporidium* and *Giardia* requirements can essentially be waived with six months of storage coupled with specific filtration and disinfection requirements. SAT is also an effective treatment barrier for the removal of bulk organic matter and TOrCs. For example, a tertiary effluent spreading operation in Arizona achieved greater than 75% removal of dissolved organic carbon (DOC)—comparable to surface waters in the region—and nearly complete removal of a wide range of TOrCs with six months of travel time (Amy & Drewes 2007). Similar results were observed during a research study in the aforementioned Montebello Forebay with only two months of travel time (Laws *et al*. 2011).

Potable reuse with membranes, ozone, and biological activated carbon

Although conventional wastewater facilities with tertiary filtration and disinfection can provide reliable source waters for potable reuse, the risk of adverse human health effects can be reduced even further with advanced treatment trains. Excluding FAT, the most common advanced treatment trains include some combination of membrane filtration, ozonation, and/or biological activated carbon (BAC). These unit processes have a number of synergistic benefits that make them competitive with RO-based treatment trains. Namely, the combination of ozone and BAC allows for significant transformation of effluent organic matter, TOrC oxidation, and more efficient biodegradation of bulk and trace organics, including potentially toxic oxidation byproducts (Stalter *et al*. 2010). The primary limitations of this treatment paradigm include the potential formation of bromate and N-nitrosodimethylamine (NDMA) during ozonation (Hollender *et al.* 2009), the inability to reduce total dissolved solids, and practical limits on total organic carbon (TOC) removal. A variety of treatment train examples (critical unit processes only) are illustrated in Figure 3 and are described in greater detail below.

The Upper Occoquan Service Authority in Fairfax County, Virginia services the Washington, D.C. metropolitan area and has been operating since 1978. The 2.0×10^5 m^3/d Regional Water Reclamation Plant employs preliminary treatment, primary treatment, and secondary treatment with conventional activated sludge targeting high SRTs (16-20 days), nitrification, and partial denitrification. Following the conventional wastewater treatment train, the facility is supplemented with lime softening for phosphorus removal, two-stage recarbonation and clarification, multimedia filtration, granular activated carbon (GAC) with a 22-min empty bed contact time (EBCT), and chlorination/dechlorination (Figure 3A). This treatment train produces a finished effluent that meets all U.S. EPA drinking water standards. The facility is also equipped with its own carbon regeneration facilities (to primarily target GAC instead of BAC), which are operated one to two times per year to reactivate approximately $2x10^6$ kg of carbon. The 48 GAC contactors are operated to achieve an effluent chemical oxygen demand (COD) of 10 mg/L and TOC concentration of approximately 3 mg/L. This level of removal of effluent organic matter is possible due to the consistent regeneration of the carbon media, which restores its adsorptive capacity. Without regeneration, it might be necessary to implement ozonation to optimize the process for biodegradation (Lee *et al.* 2009). The facility discharges the finished effluent into Bull Run Creek and ultimately the Occoquan Reservoir, which is the source water for the Fairfax County Water Authority that services some of the suburbs of the Washington, D.C. Metropolitan Area. The finished effluent generally comprises about 5% of the total inflows into the Occoquan Reservoir, but the percentage can approach 90% during prolonged periods of dry weather. Despite this potentially high recycled water contribution (RWC), there have not been any adverse human health effects associated with the treated wastewater in more than three decades. Similar to Las Vegas and Milwaukee, the downstream drinking water treatment facility has been equipped with ozonation, and it also employs GAC.

The $4.5x10^5$ m^3/d Fred Hervey Water Reclamation Facility is operated by El Paso Water Utilities in El Paso, Texas. The facility employs activated sludge supplemented with powdered activated carbon (PAC), lime softening, media filtration, ozone disinfection (~5 mg/L), BAC with a 16-min EBCT, and chlorination prior to aquifer recharge (Figure 3B). Recharge is accomplished through a combination of injection wells and spreading basins. The PAC is added to achieve existing analytical reporting limits for regulated herbicides and pesticides, and the lime softening process targets heavy metal removal and viral inactivation. With respect to the BAC process, the carbon has only been replaced twice in 27 years of operation, although $2x10^3$ - $4x10^3$ kg of carbon are added each year to replenish the amount that is lost in the underdrains and during backwashes. According to historical data from the facility, the minimum, average, and maximum effluent TOC concentrations in 2011 were 1.8 mg/L, 3.2 mg/L, and 5.2 mg/L, respectively. This facility also complies with all U.S. EPA drinking water standards. A similar full-scale facility, albeit with biologically active sand filtration instead of BAC, was constructed in Regensdorf, Switzerland to target TOrC mitigation prior to discharge to the Furtbach Creek (Hollender *et al.* 2009). Stalter *et al*. (2010) highlighted the importance of the biological sand filtration process in removing potentially toxic oxidation byproducts. Despite its efficacy, the ozone system in Regensdorf has since been decommissioned due to decreased regulatory emphasis on TOrC mitigation in Switzerland.

The F. Wayne Hill Water Resources Center in Gwinnett County, Georgia is one of the largest UF wastewater treatment plants in the world. The facility treats approximately $2.3x10^5$ m^3/d with multiple liquid treatment trains, all of which include the following processes: preliminary screening and grit removal; primary clarification; conventional activated sludge (SRT = 11 days) with full nitrification, denitrification, and biological phosphorus removal; secondary clarification; and lime softening. One treatment train continues with recarbonation and tri-media filtration (sand, anthracite, and garnet), while another treatment train continues with strainers and UF. The benefits of UF include significant removal of nearly all pathogens and potential reductions in the concentration of effluent organic matter at the ozonation point, thereby reducing the required ozone dose. Both trains recombine for pre-ozonation at a dose of 1.0-1.5 mg/L, BAC with a 15-min EBCT, and final ozone disinfection at a dose of 1.0-1.5 mg/L. Therefore, a portion of the flow is exemplified by Figure 3C, while the remaining flow is exemplified by Figure 3D. The media in the BAC process has never been replaced or regenerated so its adsorption capacity is likely exhausted, thereby isolating the biodegradation mechanism. The effluent is discharged through a 32-km pipeline to the Chattahoochee River. After years of litigation, Gwinnett County also has a permit to discharge the highly treated effluent directly into Lake Lanier, which is the Atlanta Metropolitan Area's primary drinking water source.

A similar train is operated at the South Caboolture Water Reclamation Facility in Queensland, Australia (Figure 3C), but this treatment train includes a third ozonation step between the secondary biological process and the tertiary sand filtration process (van Leeuwen *et al*. 2003; Macova *et al*. 2010; Reungoat *et al*. 2010; Reungoat *et al*. 2012). A treatment train composed of UF, ozone/H_2O_2 (H_2O_2 added for bromate mitigation), and BAC with a 30-min EBCT was also piloted at the Reno-Stead Water Reclamation Facility in Reno, Nevada (Figure 3D without final ozonation; Gerrity *et al*. 2011a). As mentioned earlier, the Central Plant operated by the Clark County Water Reclamation District in Las Vegas, Nevada will soon be upgraded with UF and ozone for improved phosphorus removal, oxidation of estrogenic compounds and other TOrCs, and microbial inactivation (Figure 3D without BAC or final ozonation).

There are also ozone-BAC facilities in Landsborough, Queensland, Australia (Reungoat *et al.* 2012); Gerringong, New South Wales, Australia (Reungoat *et al*. 2012); and Melbourne, Victoria, Australia. The Landsborough facility is equipped with UV disinfection downstream of the ozone-BAC processes (Figure 3E), and the Gerringong facility is equipped with both MF and UV disinfection downstream of the ozone-BAC processes (Figure 3F). These post-BAC treatment steps are important for addressing the potential for bacterial regrowth during biological filtration (Gerrity *et al*. 2011a). They also provide additional barriers against protozoan parasites and other pathogens, and the UV process serves as a barrier against NDMA. The EBCTs for the BAC processes in Landsborough, Caboolture (described in the previous paragraph), and Gerringong are 9, 18, and 45 min, respectively. The Caboolture and Landsborough facilities will soon be decommissioned due to decreased demand for reuse water in the region. The Eastern Treatment Plant in Melbourne is currently being upgraded with multiple ozone processes, BAC (13-min EBCT), chlorine, and UV (Figure 3G), but the high quality effluent will only be used for non-potable uses.

Potable reuse with soil aquifer treatment and UV/H_2O_2

The 1.9×10^5 m^3/d Prairie Waters Project, which was dedicated in 2010, is operated by Aurora Water in Colorado and relies heavily on biological filtration as part of its potable reuse train. This system differs from the previous IPR examples in that the advanced treatment occurs downstream of the environmental buffer, but its novelty warrants inclusion in this summary. The facility treats a wastewater-impacted source water with riverbank filtration, aquifer storage and recovery, softening, UV/H_2O_2, media filtration, and BAC (Schimmoller 2009), as illustrated in Figure 4.

Potable reuse with microfiltration, reverse osmosis, and UV/H_2O_2

The treatment train that some would consider a potential standard for potable reuse is composed of MF, RO, and UV/H_2O_2 prior to stabilization and groundwater replenishment (Figure 5B). As mentioned earlier, this is defined as full advanced treatment (FAT) by CDPH and is the only treatment train currently permitted for groundwater injection applications in the State of California (CDPH 2013). Despite the high capital costs, O&M costs, energy consumption, and brine disposal problems associated with these advanced unit processes, RO-based trains provide substantial removal of bulk organic matter (TOC < 0.5 mg/L), nearly complete TOrC removal, and significant reductions in total dissolved solids. When operating as designed, the combination of MF, RO, and UV/H_2O_2 also provides a nearly absolute barrier against pathogens. With respect to UV/H_2O_2, the UV component is primarily intended for NDMA mitigation, while the addition of H_2O_2—3 mg/L in California—achieves AOP conditions capable of significant TOrC oxidation. In the past, CDPH regulations required direct injection applications to demonstrate 1.2-log destruction of NDMA and 0.5-log destruction of 1,4-dioxane. Recent revisions allow for alternative measures of regulatory compliance, but the treatment goals are still similar (CDPH 2013). Another critical requirement of the CDPH regulations is the aforementioned 12-10-10 log removal requirement (from raw wastewater to compliance point) for viruses, *Cryptosporidium*, and *Giardia*, respectively.

The benchmark MF-RO-UV/H_2O_2 system is Orange County Water District (OCWD)'s 2.6×10^5 m^3/d Advanced Water Purification Facility, which is part of the larger Groundwater Replenishment System. Due to the success of this system, OCWD is now constructing a 1.1×10^5 m^3/d expansion to increase the capacity to 3.8×10^5 m^3/d. In addition to the potable reuse application, subsurface injection of the product water serves as an effective seawater intrusion barrier. Until recently, the West Basin Municipal Water District in California operated a 1.1×10^5 m^3/d facility with the same treatment train.

There are also several variations to this treatment scheme. The City of San Diego operated an MF-RO-UV/H_2O_2 demonstration facility to validate the process for reservoir augmentation in California. The demonstration facility was necessary because California has only implemented groundwater injection or spreading applications to date, and there are currently no regulations addressing the reservoir augmentation alternative. The concept, which has received conditional approval from CDPH, would involve pumping of product water 35 km prior to discharge into the drinking water reservoir. The City of San Diego recently published the results from its Water Purification Demonstration Project, and all parameters were well below their respective notification levels (NLs) and in compliance with U.S. EPA drinking water standards (City of San Diego [CSD] 2012).

Queensland, Australia initiated a massive infrastructure improvement project to augment its water portfolio in the wake of severe drought conditions in the early 2000s. The Western Corridor Recycled Water Project includes three MF-RO-UV/H_2O_2 facilities (Luggage Point, Bundamba, and Gibson Island) with a combined design capacity of 2.3×10^5 m^3/d (Solley *et al.* 2010). As mentioned earlier, these facilities have been used exclusively for industrial applications as a result of insufficient political and public support. The intent was to divert flows to a reservoir for potable reuse in the event of future water shortages (i.e., total reservoir storage <40%), but the facilities may be shut down entirely due to their high operational costs and reduced demand for alternative water supplies.

Due to uncertainty in long-term water availability, the Public Utilities Board in Singapore also developed a potable reuse network composed of five total facilities (four in operation). In these facilities, secondary effluent is treated with MF-RO-UV (no H_2O_2) and is then stabilized prior to industrial reuse or discharge to a drinking water reservoir (Figure 5A). Although 'NEWater' is discharged to the reservoir and then treated at a separate drinking water facility, the MF-RO-UV product satisfies all World Health Organization (WHO) requirements and is considered safe to drink by the Public Utilities Board (PUB) (PUB 2012). In the U.S., the Water Replenishment District of Southern California currently employs an MF-RO-UV train at its Leo J. Vander Lans facility for groundwater replenishment and as a seawater intrusion barrier, but the facility is being expanded and upgraded with UV/H_2O_2 to comply with CDPH regulations. A UF-RO-UV facility is also anticipated to be in operation by 2015 in Perth, Western Australia.

The Scottsdale Water Campus in Arizona, which is currently being expanded to 7.6×10^4 m^3/d, employs ozone-MF-RO-UV prior to stabilization and groundwater replenishment (del Pino & Durham 1999) (Figure 5C). The ozone process was recently added for bulk organic matter transformation and additional TOrC mitigation. Similarly, West Basin Municipal Water District's Edward C. Little Water Recycling Facility in El Segundo, California was recently upgraded with ozonation to supplement its existing MF-RO-UV/H_2O_2 treatment train (H_2O_2 included to comply with CDPH requirements) (Figure 5D). The ozone units were installed immediately upstream of MF in an effort to reduce membrane fouling (Stanford *et al*. 2011) and to increase the capacity of the plant. The ozonation step will also provide ancillary benefits in the form of reduced pathogen and TOrC loadings to the RO membrane, which will ultimately improve the quality of the RO concentrate that is discharged to the ocean (Pisarenko *et al*. 2012).

In the U.S., recent revisions to the CDPH Groundwater Replenishment Reuse regulations now allow for the possibility of replacing UV/H_2O_2 with ozone/H_2O_2 (H_2O_2 added to induce ozone conversion to OH radicals) in FAT applications (Figure 5E). Specifically, compliance has transitioned from a 1.2-log removal requirement for NDMA to a notification level of 10 ng/L. Therefore, ozone/H_2O_2 may be a viable alternative when chloramine-induced NDMA formation upstream of the RO process can be controlled without downstream UV photolysis. This alternative was recently tested at pilot-scale at the Donald C. Tillman Water Reclamation Plant in Los Angeles, California. Based on this preliminary testing, ozone/H_2O_2 appears to be a viable and more energy efficient alternative to UV/H_2O_2 (Tiwari *et al*. 2012). Future treatment trains may also employ nanofiltration (NF) as an alternative to RO since NF provides significant reductions in bulk organic matter, pathogens, and divalent ions (e.g., calcium and magnesium).

Potable reuse without environmental buffers (or direct potable reuse)

Potable reuse has generally included some type of environmental buffer, but conditions in certain areas have created an urgent need for more direct alternatives. The classic example is Windhoek, Namibia. This system has been blending treated wastewater with raw water sources since 1968, although the treatment train has been upgraded several times since its inception (Tchobanoglous *et al*. 2011). The initial barrier in this system involves extensive source control in which industrial contributions to the potable reuse facility are minimized (du Pisani 2006). In addition, the potable reuse contribution rarely exceeds 35% of the total supply—similar to the RWC concept in California (CDPH 2013)—and extensive testing of the wastewater source is also employed to identify unexpected spikes in contaminants (du Pisani 2006). The treatment train is equipped with multiple barriers for a variety of contaminant classes, such as microbes, chemicals, and aesthetic parameters, and standby processes, such as PAC, are available in the event of contaminant surges or operational inefficiencies (du Pisani 2006). The quality of the final product water is evaluated against several sets of drinking water guidelines, including the Namibian Guidelines, U.S. EPA, European Union, WHO, and Rand Water in South Africa (du Pisani 2006; Lahnsteiner & Lempert 2007). If the water does not meet established 'target' criteria, monetary penalties are enacted against the manager of the facility (du Pisani 2006), and if the water fails to meet 'absolute' criteria, it is not pumped into the distribution system (Tchobanoglous *et al.* 2011). Although the system does not include a formal engineered storage buffer, the extensive monitoring and critical control points provide a similar outcome—a buffer with sufficient storage time to allow for on-line and off-line water quality testing, analysis, and relevant decision-making.

Treated effluent from the Gammams Wastewater Treatment Plant is initially blended with raw water from the Goreangab Dam. The blended water is then treated at the New Goreangab Water Reclamation Plant with PAC (if necessary); pre-ozone; coagulation/flocculation with acid, ferric chloride, and polymer; dissolved air flotation; rapid sand filtration with potassium permanganate and sodium hydroxide; ozone with downstream H_2O_2 addition; BAC; GAC; UF; chlorination; and stabilization with sodium hydroxide (du Pisani 2006; Tchobanoglous *et al.* 2011) (Figure 6A). As mentioned earlier, the terms 'biological' and 'granular' refer to the dominant mechanisms in each process (i.e., biodegradation and adsorption for BAC and GAC, respectively). Adsorptive capacity in the GAC process is restored through regeneration of the carbon media.

As with the previous potable reuse examples, the consumption of drinking water from the Windhoek system has not been directly associated with any adverse human health impacts. The conclusions from this absence of data are also supported by scientific studies. One paper reported that the advanced treatment train eliminated all viruses from the feed water (Nupen 1970), although the sensitivity of virus detection methods has increased since the study's publication in 1970.

Currently, there are two examples of potable reuse without environmental buffers in the early stages of implementation in the U.S. The first example is Cloudcroft, New Mexico where dramatic weekend increases in population make it difficult for the mountain community to meet potable water demands strictly with its spring and well supply (Tchobanoglous *et al.* 2011). As a result, the community developed a 379 m^3/d potable reuse system. Cloudcroft can essentially be described as an advanced wastewater treatment train and an advanced drinking water treatment train separated by a blending step. On the wastewater side, the treatment train consists of a membrane bioreactor (MBR), RO, and UV/H_2O_2. The water is then blended with >51% spring or well water and stored for two weeks in a covered storage tank (i.e., the engineered storage buffer). On the drinking water side, the water is subsequently treated with UF, UV disinfection, GAC, and chlorination prior to potable distribution (Tchobanoglous *et al*. 2011). This treatment train is illustrated in Figure 6B.

The second U.S. example is the 9.5×10^3 m^3/d system in Big Spring, Texas, which is the first project implemented by the Colorado River Municipal Water District as part of a larger reuse initiative (Tchobanoglous *et al.* 2011). The Big Spring system essentially follows the California model in that FAT is implemented on the wastewater side, the product is blended with a diluent water (RWC<15%), and the water is finally treated at a conventional drinking water treatment facility. This system is scheduled to begin operation in 2013 after careful review by the Texas Commission for Environmental Quality (Tchobanoglous *et al.* 2011). The system also includes a bypass configuration if any critical control points fail to satisfy specified operational criteria (e.g., turbidity in the disinfection tertiary effluent, turbidity in the MF filtrate, conductivity in the RO permeate, and UV intensity within the UV/H_2O_2 reactor). Direct potable reuse systems are being considered in other parts of Texas as well.

Distribution systems

One of the critical elements of any RO-based treatment train is product water stabilization. Product water stabilization is the augmentation of hardness and alkalinity with chemical additions, such as lime, calcium hydroxide, calcium carbonate, or calcium chloride, to prevent corrosion of pipelines and leaching of substances from the environment. Product water stabilization also provides an opportunity to improve the taste of the product water by adjusting mineral concentrations based on customer preferences. Therefore, potable reuse has the potential to offer a 'bottled-water experience' in a more affordable and sustainable manner, despite being traceable to its wastewater origin.

While over-looked in many discussions of potable reuse, it is important to highlight the potential problems associated with the distribution system. Although the potable reuse treatment train is essentially capable of removing all contaminants of concern to undetectable levels, a poorly maintained distribution system compromises that high level of quality and creates conditions conducive to opportunistic pathogens and pathogen intrusion (Wingender & Flemming 2011; Biyela *et al*. 2012; Buse *et al.* 2012). With the exception of corrosivity issues with RO permeate, it is unclear whether potable reuse would pose any unique challenges compared to conventional potable distribution systems, but it is an issue that should be considered in the development of public health criteria.

CONCLUSION

Potable reuse is becoming an increasingly common strategy for bolstering water resource portfolios in water-scarce regions. Each application poses unique challenges, whether related to treatment goals, regulatory requirements, or political and public acceptance, and these issues have a significant impact on the final treatment train selection. This is evident in the wide range of treatment trains described above. Ultimately, public health is the most critical factor in characterizing the success of a particular paradigm or treatment train. Due to the focus on conservative designs and redundancy in early projects, proper operation and maintenance of advanced systems has been sufficient to ensure public health even when using raw sewage as a source water for direct potable reuse applications.

Significant emphasis has been placed on the ubiquity of TOrCs in wastewater, but it is likely that only a small number of recalcitrant contaminants (e.g., NDMA) will control the design of advanced treatment facilities in the future. In many cases, pathogen removal requirements will drive unit process selection and integration, and in other cases, traditional disinfection byproducts, such as trihalomethanes and bromate, may dictate the required level of treatment. With the elimination of environmental buffers and the shift toward closed-loop water systems, inevitable increases in total dissolved solids may necessitate some degree of high-pressure membrane filtration (i.e., NF or RO). However, the combination of ozone and biological filtration offers a viable and potentially more sustainable alternative to RO-based trains in many applications. Most water agencies have access to the entire 'toolbox' of potable reuse paradigms illustrated in this paper unless they are limited by prescriptive regulatory frameworks or site-specific water quality issues.

Although critically important, health-based goals are only one component of treatment train selection. In a world where the water-energy nexus is becoming increasingly important, energy efficiency must be taken into consideration when selecting a treatment train. It is clear that many of the treatment trains described above consume a significant amount of energy, and this is compounded by the overall O&M and capital costs associated with advanced treatment. Despite these limitations, urban communities cannot thrive without sufficient water supplies so these investments are certainly warranted in many situations. Furthermore, preliminary evidence indicates that some applications will either be comparable or potentially more cost and energy efficient than traditional water importation (Leverenz *et al.* 2011; Sloan 2011).

Advanced treatment trains are technically capable of transforming raw sewage into a higher quality product than those produced by many traditional sources and conventional treatment. However, there is always potential for process breakdowns and/or surges in contaminant loadings. Robustness, resiliency, and redundancy are integrated into existing trains to address this concern, but the industry also needs improved technologies for on-line monitoring and process control. With respect to pathogens, standard microbiological methods are unable to reliably identify the presence of infectious agents within a desired timeframe. Although engineered storage buffers address this issue to some degree, technologies that accomplish such goals in real-time would be a tremendous asset to the industry and would provide further protection of public health. In the meantime, the potential for failure can be minimized by included extra redundancy. The industry has begun to develop an effective framework for potable reuse, but there are still issues that need to be addressed to further validate the suitability and safety of the concept.

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REFERENCES

Amy, G. & Drewes, J. 2007 Soil aquifer treatment (SAT) as a natural and sustainable wastewater reclamation/reuse technology: Fate of wastewater effluent organic Matter (EfOM) and trace organic compounds. *Environ. Monit. Assess*. **129**(1–3), 19–26.

Asano, T., Burton, F.L., Leverenz, H.L., Tsuchihashi, R. & Tchobanoglous, G. 2007 *Water Reuse: Issues, Technologies, and Applications*. McGraw-Hill, New York.

Biyela, P.T., Ryu, H., Brown, A., Alum, A., Abbaszadegan, M. & Rittmann, B.E. 2012 Distribution systems as reservoirs of Naegleria fowleri and other amoebae. *J. Am. Wat. Works Assoc*. **104**, 49–50.

Bull, R.J., Crook, J., Whittaker, M. & Cotruvo, J.A. 2011 Therapeutic dose as the point of departure in assessing potential health hazards from drugs in drinking water and recycled municipal wastewater. *Reg. Toxicol. Pharmacol*. **60**, 1–19.

Buse, H.Y., Schoen, M.E. & Ashbolt, N.J. 2012 Legionellae in engineered systems and use of quantitative microbial risk assessment to predict exposure. *Wat. Res.* **46**, 921–933.

Carmichael, W.W., Azevedo, S.M.F.O., An, J.S., Molica, R.J.R., Jochimsen, E.M., Lau, S., Rinehard, K.L., Shaw, G.R. & Eaglesham, G.K. 2001 Human fatalities from cyanobacteria: Chemical and biological evidence for cyanotoxins. *Environ. Health Perspect.* **109**, 663–668.

CDPH 2013 *Groundwater Replenishment Reuse Draft Regulations*. California Department of Public Health. Sacramento, CA. <http://www.cdph.ca.gov/healthinfo/environhealth/water/pages/waterrecycling.aspx>. Accessed: Feb. 17, 2013.

Crittenden, J.C., Trussell, R.R., Hand, D.W., Howe, K.J. & Tchobanoglous, G. 2005 *Water Treatment: Principles and Design*. John Wiley & Sons, Inc., Hoboken, NJ.

CSD 2012 *Advanced Water Purification Demonstration Facility Preliminary Water Quality Monitoring Results*. City of San Diego. <http://www.sandiego.gov/water/waterreuse/pdf/awpdfwebdata120424.pdf>. Accessed: Feb. 17, 2013.

del Pino, M.P. & Durham, B. 1999 Wastewater reuse through dual-membrane processes: Opportunities for sustainable water resources. *Desalination* **124**, 271–277.

Dominguez-Chicas, A. & Scrimshaw, M.D. 2010 Hazard and risk assessment for indirect potable reuse schemes: An approach for use in developing Water Safety Plans. *Wat. Res*. **44**, 6115–6123.

Drewes, J.E., Hoppe, C., Heil, D. & Dickenson, E. 2010 *Performance Assessment of Surface Spreading Operations Receiving Different Blends of Tertiary/RO Treated Waters*. Final Report to the Water Replenishment District of Southern California.

du Pisani, P.L. 2006 Direct reclamation of potable water at Windhoek's Goreangab reclamation plant. *Desalination* **188**, 79–88.

EPA 2001 *Cryptosporidium: Human Health Criteria Document*. EPA-822-K--94-001. Office of Science and Technology and Office of Water, Washington, DC. United States Environmental Protection Agency. <http://water.epa.gov/action/advisories/drinking/upload/2009_02_03_criteria_humanhealth_microbial_crypto.pdf>. Accessed: Feb. 17, 2013.

EPA 2012 *Guidelines for Water Reuse*. EPA/600/R-12/618. Office of Water, Washington, DC. United States Environmental Protection Agency. <http://nepis.epa.gov/Adobe/PDF/P100FS7K.pdf>. Accessed: Feb. 17, 2013.

Freeman, S., Bates, J., Wallis-Lage, C. & McEvoy, J. 2008 Drought relief in south east, Queensland, Australia, provided by membrane-reclaimed water. *J. Am. Wat. Works Assoc*. **100**(2), 40–52.

Gerrity, D., Gamage, S., Holady, J.C., Mawhinney, D.B., Quinones, O., Trenholm, R.A. & Snyder, S.A. 2011a Pilot-scale evaluation of ozone and biological activated carbon for trace organic contaminant mitigation and disinfection. *Wat. Res.* **45**, 2155–2165.

Gerrity, D., Holady, J.C., Mawhinney, D.B., Quinones, O., Trenholm, R.A. & Snyder, S.A. 2013 The effects of solids retention time in full-scale activated sludge basins on trace organic contaminant concentrations. *Wat. Environ. Res*. **85**(8), 715–724.

Gerrity, D. & Snyder, S.A. 2011 Review of ozone for water reuse applications: Toxicity, regulations, and trace organic contaminant oxidation. *Ozone Sci. Eng.* **33**, 253–266.

Gerrity, D., Trenholm, R.A. & Snyder, S.A. 2011b Temporal variability of pharmaceuticals and illicit drugs in wastewater and the effects of a major sporting event. *Wat. Res*. **45**, 5399–5411.

Goldstein, S.T., Juranek, D.D., Ravenholt, O., Hightower, A.W., Martin, D.G., Mesnik, J.L., Griffiths, S.D., Bryant, A.J., Reich, R.R. & Herwaldt, B.L. 1996 Cryptosporidiosis: An outbreak associated with drinking water despite state-of-the-art water treatment. *Ann. Intern. Med.* **124**, 459–468.

Hollender, J., Zimmermann, S.G., Koepke, S., Krauss, M., McArdell, C.S., Ort, C., Singer, H., von Gunten, U. & Siegrist, H. 2009 Elimination of organic micropollutants in a municipal wastewater treatment plant upgraded with a full-scale post-ozonation followed by sand filtration. *Environ. Sci. Technol.* **43**(20), 7862–7869.

Joss, A., Keller, E., Alder, A.C., Gobel, A., McArdell, C.S., Ternes, T. & Siegrist, H. 2005 Removal of pharmaceuticals and fragrances in biological wastewater treatment. *Wat. Res*. **39**, 3139–3152.

Lahnsteiner, J. & Lempert, G. 2007 Water management in Windhoek, Namibia. *Wat. Sci. Technol*. **55**, 441–448.

Laws, B.V., Dickenson, E.R.V., Johnson, T.A., Snyder, S.A. & Drewes, J.E. 2011 Attenuation of contaminants of emerging concern during surface-spreading aquifer recharge. *Sci. Total Environ*. **409**(6), 1087–1094.

Lee, L.Y., Ng, H.Y., Ong, S.L., Hu, J.Y., Tao, G., Kekre, K., Viswanath, B., Lay, W. & Seah, H. 2009 Ozone-biological activated carbon as a pretreatment process for reverse osmosis brine treatment and recovery. *Wat. Res*. **43**(16), 3948–3955.

Leverenz, H.L., Tchobanoglous, G. & Asano, T. 2011 Direct potable reuse: A future imperative. *J. Wat. Reuse Desalin*. **1**(1), 2–10.

MacKenzie, W.R., Hoxie, N.J., Proctor, M.E., Gradus, M.S., Blair, K.A., Peterson, D.E., Kazmierczak, J.J., Addiss, D.G., Fox, K.R., Rose, J.B. & Davis, J.P. 1994 A massive outbreak in Milwaukee of Cryptosporidium infection transmitted through the public water supply. *New Eng. J. Med*. **331**, 161–167.

Macova, M., Escher, B.I., Reungoat, J., Carswell, S., Chue, K.L., Keller, J. & Mueller, J.F. 2010 Monitoring the biological activity of micropollutants during advanced wastewater treatment with ozonation and activated carbon filtration. *Wat. Res.* **44**, 477–492.

Marks, J. 2006 Taking the public seriously: The case of potable and non potable reuse. *Desalination* **187**, 137–147.

Marks, J., Martin, B. & Zadoronznyi, M. 2006 Acceptance of water recycling in Australia: National baseline data. *Water* **33**, 151–157.

NDEP 2001 *The Lake Mead Algal Bloom of 2001*. Nevada Division of Environmental Protection. <http://ndep.nv.gov/forum/docs/LM_algalbloom_2001.pdf>. Accessed: Feb. 17, 2013.

Nelson, E.D., Do, H., Lewis, R.S. & Carr, S.A. 2011 Diurnal variability of pharmaceutical, personal care product, estrogen and alkylphenol concentrations in effluent from a tertiary wastewater treatment facility. *Environ. Sci. Technol*. **45**, 1228–1234.

NRC 1998 I*ssues in Potable Reuse: The Viability of Augmenting Drinking Water Supplies with Reclaimed Water*. National Research Council. National Academies Press. Washington, DC. <http://www.nap.edu/catalog.php?record_id=6022>. Accessed: Feb. 17, 2013.

NRC 2008 *Mississippi River Water Quality and the Clean Water Act: Progress, Challenges, and Opportunities*. National Research Council. National Academies Press. Washington, DC. <http://www.nap.edu/catalog.php?record_id=12051>. Accessed: Feb. 17, 2013.

NRC 2012 *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater.* National Research Council. National Academies Press. Washington, DC. <http://www.nap.edu/catalog.php?record_id=13303>. Accessed: Feb. 17, 2013.

Nupen, E.M. 1970 Virus studies on the Windhoek waste-water reclamation plant (South-west Africa). *Wat. Res*. **4**, 661–672.

Oneby, M.A., Bromley, C.O., Borchardt, J.H. & Harrison, D.S. 2010 Ozone treatment of secondary effluents at U.S. municipal wastewater treatment plants. *Ozone Sci. Eng*. **32**, 43–55.

Ort, C., Lawrence, M.G., Reungoat, J. & Mueller, J.F. 2010 Sampling for PPCPs in wastewater systems: Comparison of different sampling modes and optimization strategies. *Environ. Sci. Technol.* **44**, 6289–6296.

Pisarenko, A.N., Stanford, B.D., Yan, D., Gerrity, D. & Snyder, S.A. 2012 Effects of ozone and ozone/peroxide on trace organic contaminants and NDMA in drinking water and water reuse applications. *Wat. Res*. **46**, 316–326.

Plosz, B.G., Leknes, H., Liltved, H. & Thomas, K.V. 2010 Diurnal variations in the occurrence and the fate of hormones and antibiotics in activated sludge wastewater treatment in Oslo, Norway. *Sci. Total Environ*. **408**, 1915–1924.

Postigo, C., Lopez de Alda, M. & Barcelo, D. 2011 Evaluation of drugs of abuse and trends in a prison through wastewater analysis. *Environ. Int.* **37**, 49–55.

PUB 2012 *NEWater: The 3rd National Tap*. Singapore Public Utilities Board. <http://www.pub.gov.sg/water/newater/Pages/default.aspx>. Accessed: Feb. 17, 2013.

Reungoat, J., Escher, B.I., Macova, M., Argaud, F.X., Gernjak, J.K. & Keller, J. 2012 Ozonation and biological activated carbon filtration of wastewater treatment plant effluents. *Wat. Res.* **46**, 863–872.

Reungoat, J., Macova, M., Escher, B.I., Carswell, S., Mueller, J.F. & Keller, J. 2010 Removal of micropollutants and reduction of biological activity in a full scale reclamation plant using ozonation and activated carbon filtration. *Wat. Res*. **44**, 625–637.

Reynolds, K.A., Mena, K.D. & Gerba, C.P. 2008 Risk of waterborne illness via drinking water in the United States. *Rev. Environ. Contam. Toxicol.* **192**, 117–158.

Rock, C., Solop, F.I. & Gerrity, D. 2012 Survey of statewide public perceptions regarding water reuse in Arizona. *J. Wat. Supply Res. Technol. AQUA* **61**, 506–517.

Schimmoller, L. 2009 *Treatment of Microconstituents for Water Reuse and Drinking Water Applications*. Pacific Northwest Section of the American Water Works Association. <http://www.pnws-awwa.org/uploads/PDFs/conferences/2009/Schimmoller_PPCP_Treatment.pdf>. Accessed: Feb. 17, 2013.

Sim, W.J., Lee, J.W., Lee, E.S., Shin, S.K., Hwang, S.R. & Oh, J.E. 2010 Occurrence and distribution of pharmaceuticals in wastewater from households, livestock farms, hospitals and pharmaceutical manufactures. *Chemosphere* **82**, 179–186.

Sim, W.J., Lee, J.W., Shin, S.K., Song, K.B. & Oh, J.E. 2011 Assessment of fates of estrogens in wastewater and sludge from various types of wastewater treatment plants. *Chemosphere* **82**, 1448–1453.

Sloan, D.W. 2011 *Potable Reuse in the Permian Basin*. Water Environment Association of Texas. San Antonio, TX. <http://www.weat.org/sanantonio/files/09%20DavidSloanSummerSeminar2011.pdf >. Accessed: Feb. 17, 2013.

Sloss, E.M., Geschwind, S.A., McCaffrey, D.F. & Ritz, B.R. 1996 *Groundwater Recharge with Reclaimed Water: An Epidemiologic Assessment in Los Angeles County, 1987-1991*. Rand, Santa Monica, CA.

Sloss, E.M., McCaffrey, D.F., Fricker, R.D., Geschwind, S.A. & Ritz, B.R. 1999 *Groundwater Recharge with Reclaimed Water: Birth Outcomes in Los Angeles County, 1982-1993*. Rand, Santa Monica, CA.

Snyder, S., von Gunten, U., Amy, G., Debroux, J. & Gerrity, D. 2013 *Use of Ozone in Water Reclamation for Contaminant Oxidation*. Final Report for WRF-08-05. WateReuse Research Foundation. Alexandria, VA.

Solley, D., Gronow, C., Tait, S., Bates, J. & Buchanan, A. 2010 Managing the reverse osmosis concentrate from the Western Corridor Recycled Water Scheme. *Wat. Prac. Technol.* **5**, No Pag.

Stalter, D., Magdeburg, A. & Oehlmann, J. 2010 Comparative toxicity assessment of ozone and activated carbon treated sewage effluents using an in vivo test battery. *Wat. Res*. **44**(8), 2610–2620.

Stanford, B.D., Pisarenko, A.N., Holbrook, D.R. & Snyder, S.A. 2011 Preozonation effects on the reduction of reverse osmosis membrane fouling in water reuse. *Ozone Sci. Eng.* **33**, 379–388.

Takao, Y., Shimazu, M., Fukuda, M., Ishibashi, H., Nagae, M., Kohra, S., Tabira, Y., Ishibashi, Y. & Arizono, K. 2008 Seasonal and diurnal fluctuations in the concentrations of pharmaceuticals and personal care products (PPCPs) in residential sewage water. *J. Health Sci*. **54**(2), 240–243.

Tchobanoglous, G., Leverenz, H.L., Nellor, M.H. & Crook, J. 2011 *Direct Potable Reuse: A Path Forward.* WateReuse Research Foundation. WateReuse California. Alexandria, VA. <http://www.watereuse.org/product/direct-potable-reuse-path-forward>. Accessed: Feb. 17, 2013.

Tiwari, S., Hokanson, D., Stanczak, G. & Trussell, R. 2012 *Pilot-scale* UV/H_2O_2 *and* O_3/H_2O_2 *AOP performance comparison for groundwater recharge*. WateReuse California Annual Conference. Sacramento, CA.

USDOI 2003 *Water 2025: Preventing Crisis and Conflict in the West*. United States Department of the Interior. <http://www.usbr.gov/WaterSMART/>. Accessed: Feb. 17, 2013.

Vanderford, B.J. & Snyder, S.A. 2006 Analysis of pharmaceuticals in water by isotope dilution liquid chromatography/tandem mass spectrometry. *Environ. Sci. Technol*. **40**, 7312–7320.

van Leeuwen, J., Pipe-Martin, C. & Mehmann, R.M. 2003 Water reclamation at South Caboolture, Queensland, Australia. *Ozone Sci. Eng*. **25**, 107–120.

Westerhoff, P., Yoon, Y., Snyder, S. & Wert, E. 2005 Fate of endocrine-disruptor, pharmaceutical, and personal care product chemicals during simulated drinking water treatment processes. *Environ. Sci. Technol*. **39**(17), 6649–6663.

Wingender, J. & Flemming, H. 2011 Biofilms in drinking water and their role as reservoir for pathogens. *Int. J. Hygiene Environ. Health* **214**, 417–423.

Figure 1. Summary of potable reuse paradigms.

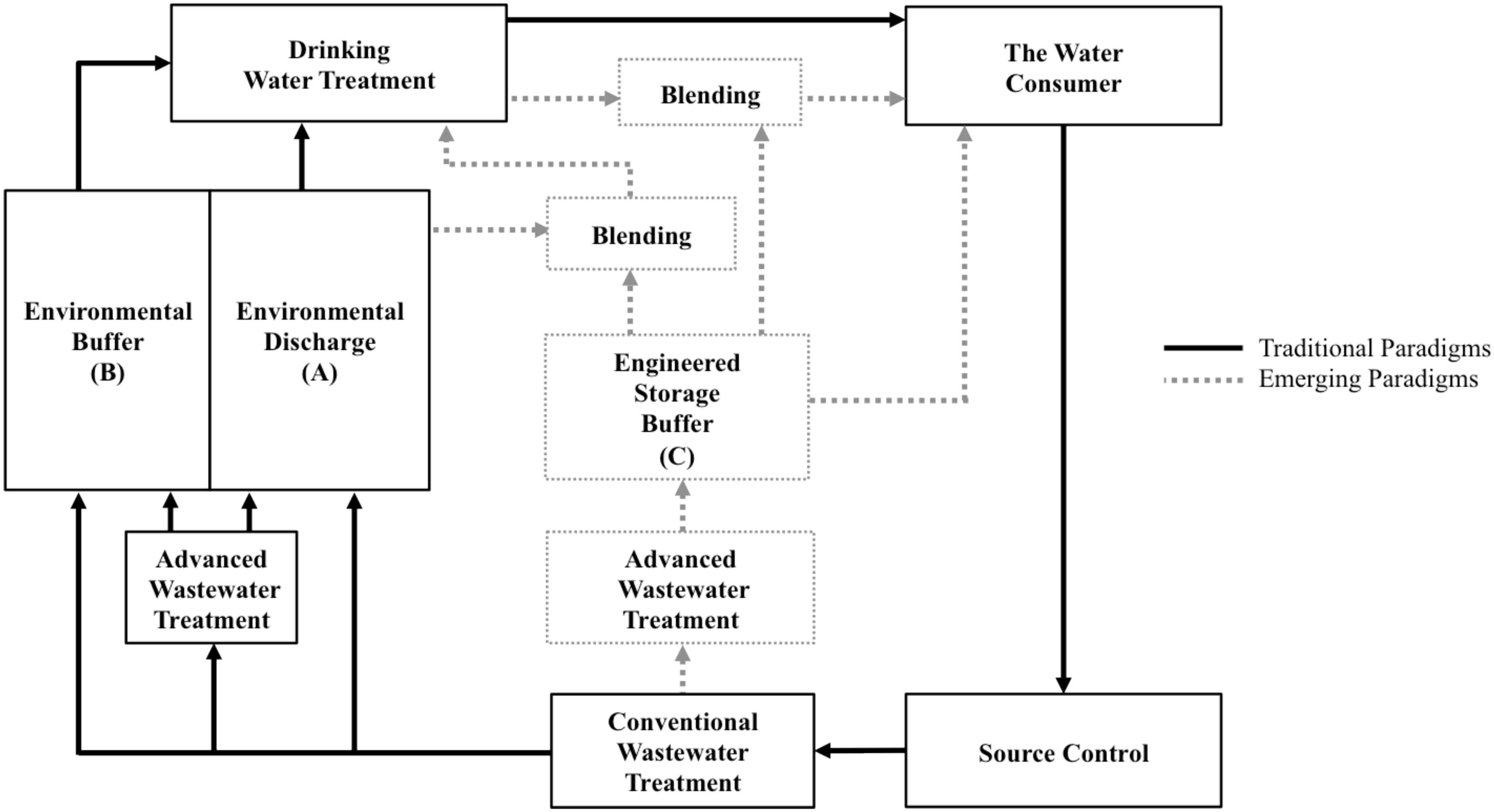


Figure 2. Conventional wastewater treatment (worst-case) for (A) *de facto* reuse and (B) "planned" potable reuse. The environmental buffer for *de facto* reuse applications is almost exclusively surface water discharge, while "planned" potable reuse involves both surface water discharge and groundwater replenishment. Groundwater replenishment applications often rely on the spreading of disinfected tertiary effluent and subsequent soil aquifer treatment (SAT) to ensure that the water is safe for consumption.

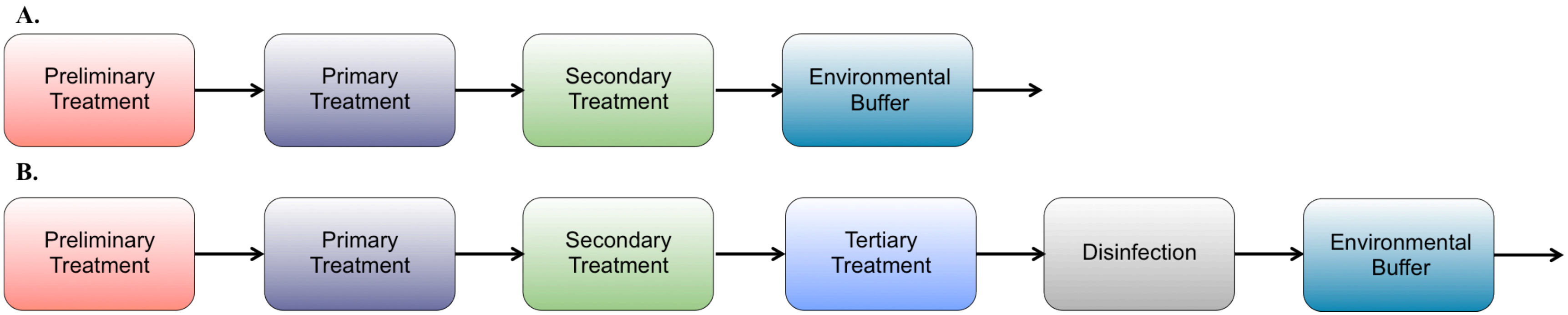
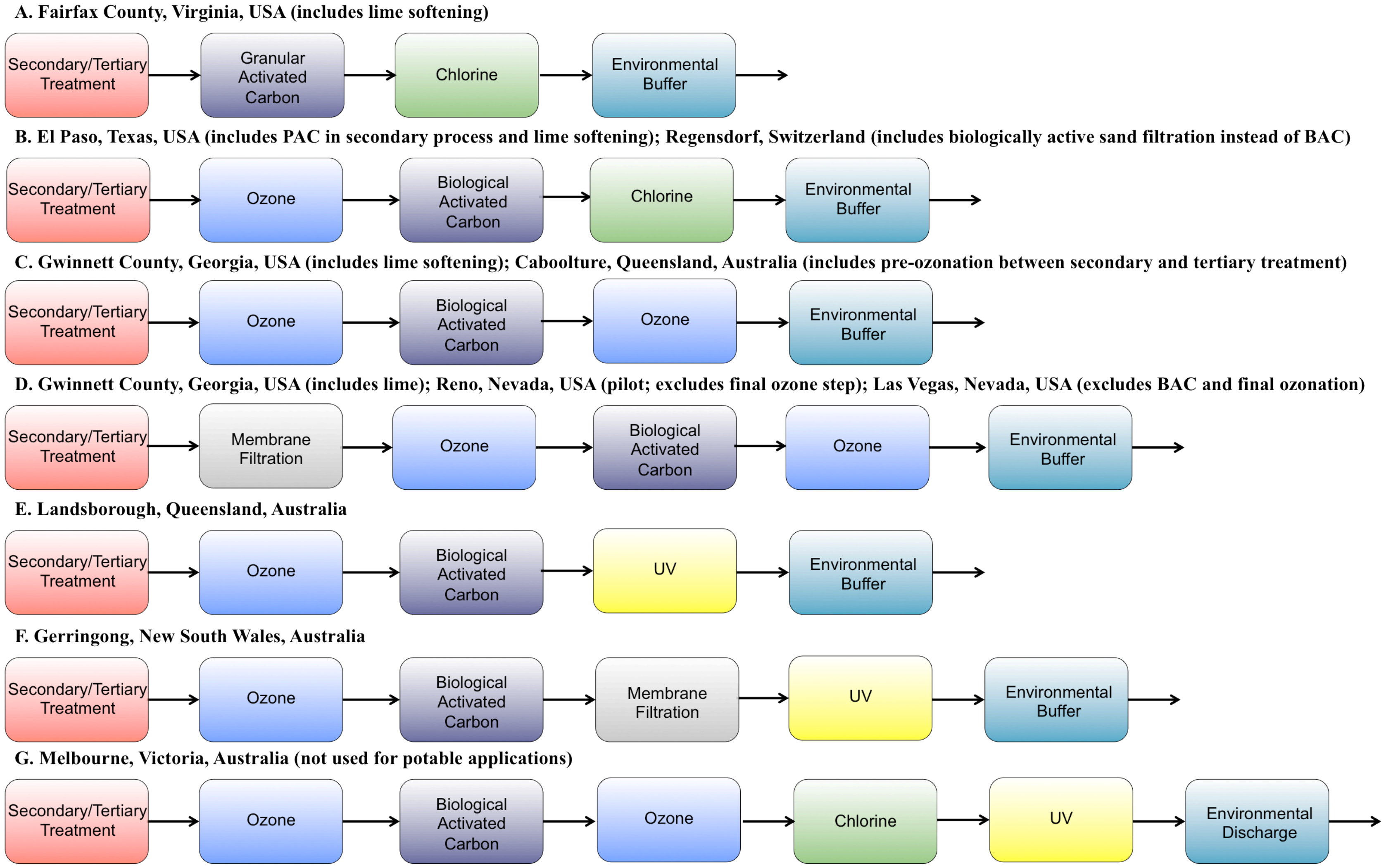


Figure 3. Potable reuse with membrane filtration, ozone, and/or activated carbon.



A. Fairfax County, Virginia, USA (includes lime softening)

B. El Paso, Texas, USA (includes PAC in secondary process and lime softening); Regensdorf, Switzerland (includes biologically active sand filtration instead of BAC)

C. Gwinnett County, Georgia, USA (includes lime softening); Caboolture, Queensland, Australia (includes pre-ozonation between secondary and tertiary treatment)

D. Gwinnett County, Georgia, USA (includes lime); Reno, Nevada, USA (pilot; excludes final ozone step); Las Vegas, Nevada, USA (excludes BAC and final ozonation)

E. Landsborough, Queensland, Australia

F. Gerringong, New South Wales, Australia

G. Melbourne, Victoria, Australia (not used for potable applications)

Figure 4. Potable reuse in the Prairie Waters Project.

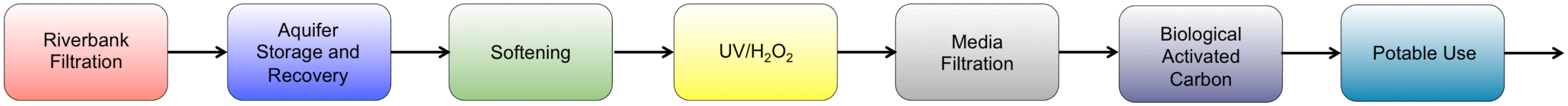
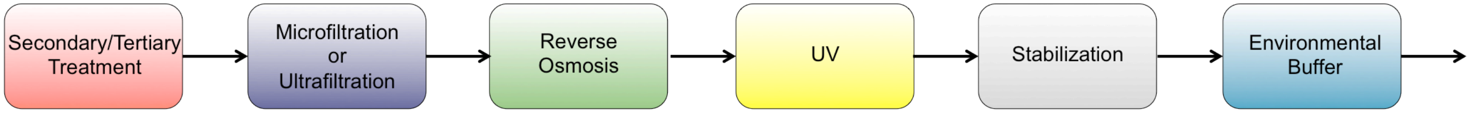
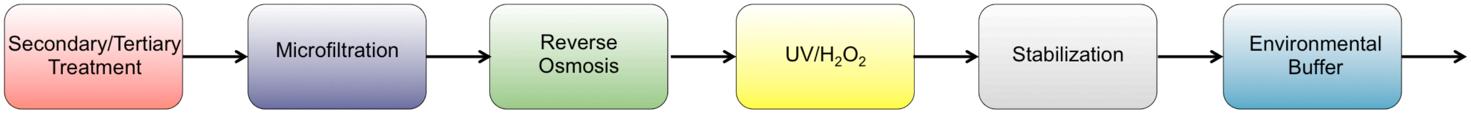


Figure 5. Potable reuse with microfiltration or ultrafiltration, reverse osmosis, and UV or advanced oxidation.

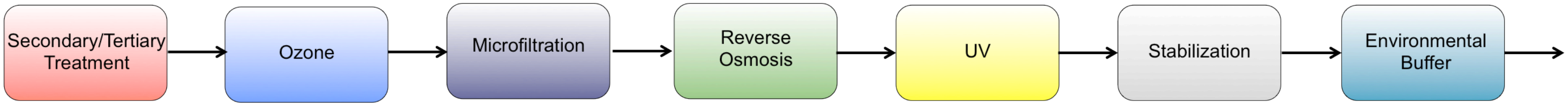
A. Los Angeles, California, USA (microfiltration); Singapore (microfiltration); Perth, Western Australia, Australia (ultrafiltration; under construction)



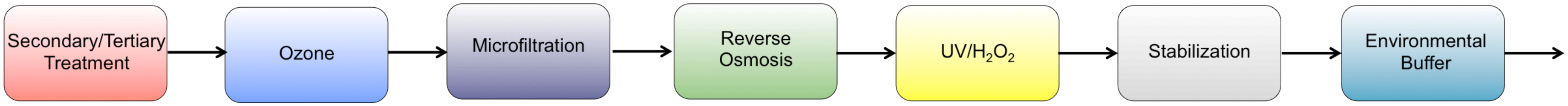
B. Orange County, California, USA; San Diego, California, USA; Queensland, Australia



C. Scottsdale, Arizona, USA



D. El Segundo, California, USA



E. Los Angeles, California, USA (pilot)

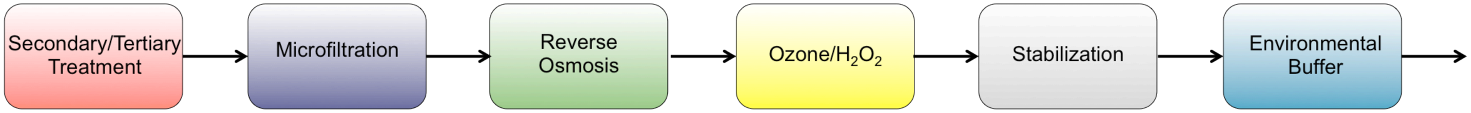
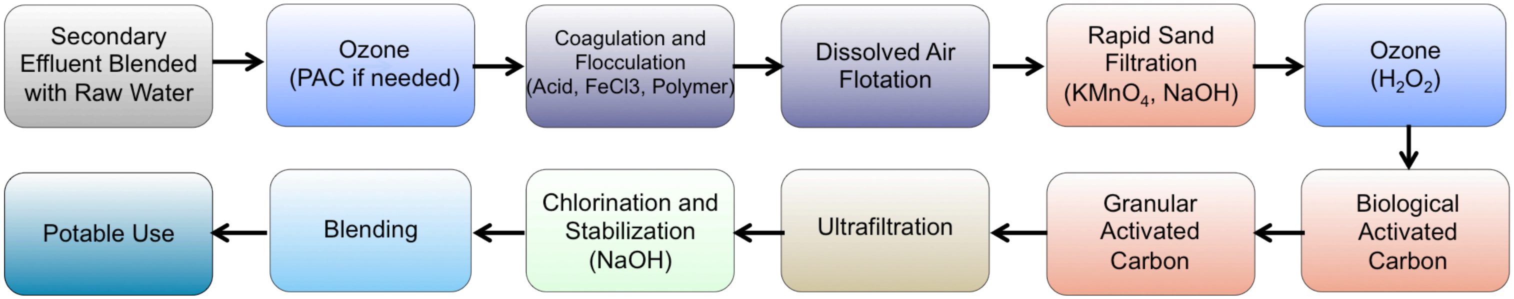
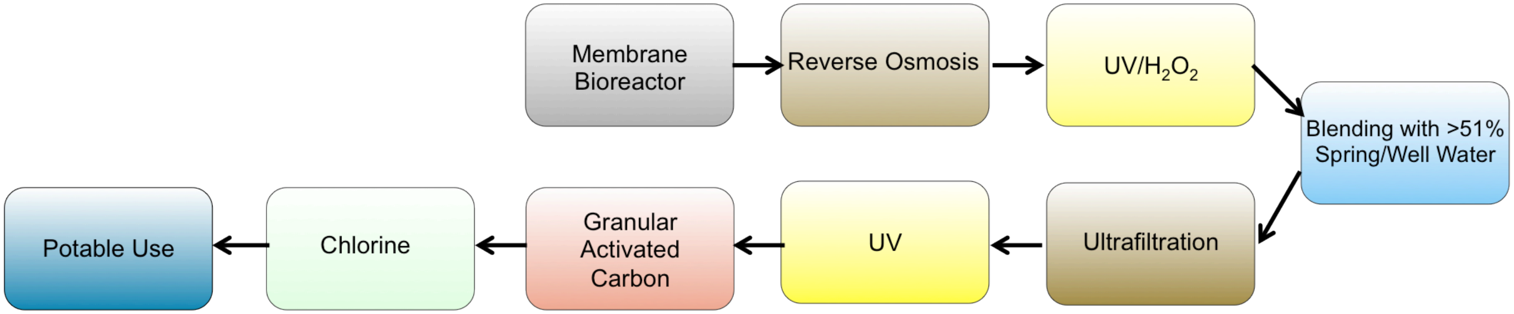


Figure 6. Potable reuse treatment trains without environmental buffers (or direct potable reuse).

A. Windhoek, Namibia



B. Cloudcroft, New Mexico



C. Big Springs, Texas