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Review of the leading challenges in maintaining reclaimed water quality during storage and distribution

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ABSTRACT

Reclaimed water quality has largely focused on meeting standards in the treated effluent. While the focus is well placed, reclaimed water may change before it is used at dispersed locations. Reclaimed water is a perishable product with a shelf life requiring packaging (i.e., piping) and preserving (with a disinfectant) during storage to minimize deterioration in quality. It typically contains higher nutrient levels compared to potable water. Based on an online survey, the challenges were characterized into nine categories in order of importance: infrastructure, water quality, customer relations, operational, cost (pricing), capacity/supply, regulation, workforce, and miscellaneous. The first five categories accounted for 80% of the challenges raised by the industry. A review of the literature provided various remedies to these challenges which can be incorporated into best management practices for controlling potential health and aesthetic issues associated with storage and distribution of reclaimed water.

Key words | algae, customer, infrastructure, pricing

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ABBREVIATIONS

A2O	anaerobic/anoxic/oxic process
AOC	assimilable organic carbon
ASTM	American Society for Testing and Materials
ATP	adenosine triphosphate
BDDA	booster disinfection design and analysis software
BDOC	biodegradable dissolved organic carbon
BOD	biochemical oxygen demand
BOM	biodegradable organic matter
CBOD	carbonaceous BOD
Cl:N	chlorine to nitrogen ratio
CLSM	confocal laser scanning microscopy
COC	cycles of concentration
COD	chemical oxygen demand
CT	contact time
DBPs	disinfection by-products
DO	dissolved oxygen
DOM	dissolved organic matter
FEEM	fluorescence excitation–emission matrices
GIS	geographic information system
GPD	gallons per day
HDPE	high-density polyethylene
HPC	heterotrophic plate count
MBR	membrane bioreactor
MLE	Modified Ludzack–Ettinger Process
NDMA	nitrosodimethylamine
NPDES	National Pollutant Discharge Elimination System
ORP	oxidation–reduction potential
PER	piping efficiency ratio
PEX	polyethylene
PP	polypropylene
PVC	polyvinyl chloride
RBC	rotating biological contactor
RO	reverse osmosis
SMCL	secondary maximum contaminant levels
SVMM	strategic valve management model
TDS	total dissolved salts
THM	trihalomethane
TOC	total organic carbon

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TrOCs trace organic compounds
USEPA United States Environmental Protection Agency
UV ultraviolet light
UVT ultraviolet light transmittance

INTRODUCTION

In the United States of America, the planned reclamation of water began almost a century ago in California and Arizona to support crop irrigation practices (Asano & Levine 1996; Asano *et al.* 2007). Since then, water reclamation has expanded to other areas of the country including urban locations. Wastewater generation and treatment are continuous processes in urban areas; however, beneficial reclamation (e.g., irrigation, golf course irrigation, aquifer recharge, surface water augmentation, etc.) may be only practiced during high demand seasons. Alternatively, treatment may occur at one location and the reclaimed water may actually be used at several geographically dispersed locations. To handle the variable demands at dispersed locations, it is often necessary for centralized treatment facilities to utilize seasonal or long-term storage in open or closed reservoirs. A survey of 71 reclaimed water utilities, within the USA and Australia identified problems characterized under nine different categories. Infrastructure issues were most frequently identified, followed by water quality, customer, operations, cost, capacity/supply, regulations, and workforce (Figure 1). Most (>80%) of the issues raised belonged to the first five categories. This finding was used to prioritize the reviewed themes as they relate to managing and operation of reclaimed water storage and distribution systems with a better understanding and possible remediation measures for the five categories. The remaining four categories are addressed in a companion paper (Jjemba *et al.* in preparation). Details about how the survey was conducted and literature sources identified are also presented in the companion paper.

INFRASTRUCTURE

Infrastructural issues are of paramount concern to reclaimed water utilities nationwide (Asano *et al.* 1996; Selvakumar & Tafuri 2012). The generic infrastructural issues identified by utilities are summarized in Table 1. They range from system designs that are unable to handle water pressure variations, poor conveyance, deterioration due to corrosion from high disinfectant residuals, metals or salts, metering and, most important, providing adequate storage of the reclaimed water. Reclaimed water infrastructure displays a high level of engineering systems. These attributes are discussed below.

Storage

Storage issues encompass the lack of redundancy in the system and challenges of conveying water to the site. Water reclamation is lowest during the daytime hours

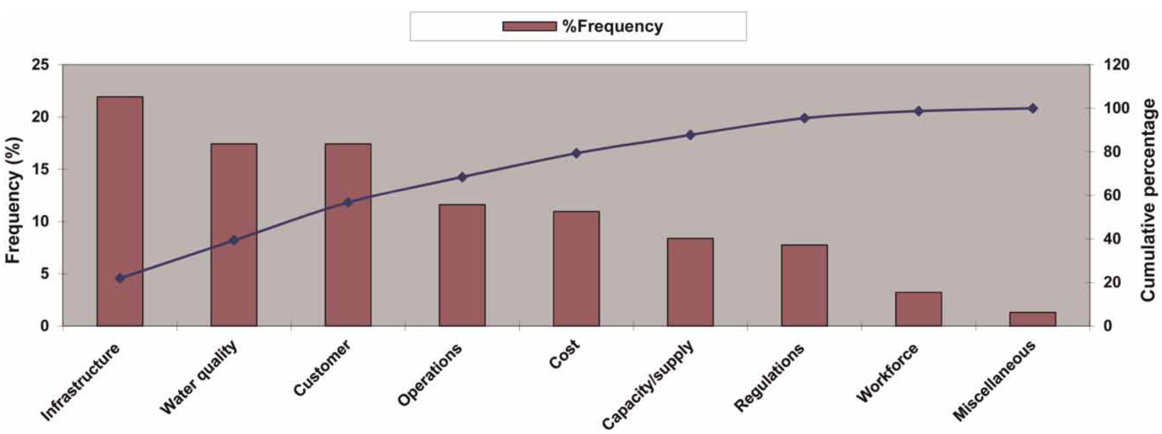

Figure 1 | Categories of issues identified by the reclaimed water industry associated with managing and maintaining water quality in reservoirs and distribution systems (based on 71 utilities; with 155 issues raised).

Table 1 | Generic infrastructural issues identified through the survey

• Distribution pressure (low, surges, or inconsistencies particularly at end of the system)	• Challenges in conveying water to recharge (or reuse) site
• Non-looped distribution system (associated with a lack of redundancy on supply)	• Frequent leaks in chlorination system (liquid feeds)
• Cost and cost-effective means to extend system to potential customers	• Damage to transmission mains
• Branched distribution system and related limitation	• Inadequate metering in cases where users may be located further apart
• Infrastructure/equipment deterioration from high chlorine residual	• High corrosivity of water impacting metal component in the distribution system
• Lack of enough storage	
• Managing cross connection (especially beyond customer meter)	

when people are active and producing wastewater but also the time when irrigation systems are generally inactive to allow for uninterrupted use of public greenbelts. Irrigation demand is much higher at night when the public is not using parks, schools, golf courses, etc., but is also not producing wastewater. Therefore, there is usually a 12 h offset between peak reclaimed water production and peak reclaimed water demand. To offset the discrepancy between wastewater generation and reclaimed water demand, reclaimed water is often kept in some form of storage system prior to use. Reservoirs may be in tanks or ponds. Because of the volumes of reclaimed water and the variation in demand, the latter form of storage is more commonly used. Management and maintenance of reclaimed water tanks include regular inspection of the foundation, as well as the outside and inside of the tank, periodic draining and removal of debris.

Reservoirs can have a critical influence on reclaimed water quality (Jjemba *et al*. 2010a). Covered reservoirs have minimal influence from direct sunlight which minimizes algal growth. By contrast, open reservoirs are exposed to direct sunlight which favors proliferation of algae and various water weeds such as duckweed (*Lemna* sp.). Presence of such vegetation may necessitate operational practices such as draining or spraying with herbicides (Rimer & Miller 2012). Fornarelli & Antenucci (2011) reported excellent results from the transferring of water from one reservoir to another to control vegetation. This practice dictates two operational decision variables, the magnitude and timing of water transfers, which should be considered for integrated management of the reservoir system. The timing of the transfer is important in controlling phytoplankton biovolume. By specifically avoiding pumping during algal bloom periods in the source reservoir, the diatom and cyanobacteria biovolume was reduced by one half in the receiving reservoir. No cyanobacteria growth was documented when transfers occurred during summer.

Corrosion and deterioration of structures

Corrosion involves the dissolution of a structure from anodic sites with the subsequent acceptance of electrons at cathodic sites. It occurs both under oxic and anoxic environments. During corrosion, the consumption of electrons varies, depending on the redox potential of the surface. Under oxic environments, oxygen serves as the electron acceptor, forming a variety of oxides and hydroxides (Jjemba 2004). At a low redox potential, protons become the electron acceptors yielding H_2 and other reduced products. In the presence of bacterial biofilms on the infrastructural surfaces, the uptake of oxygen is enhanced, creating localized zones of differential aeration. This in turn produces cathodic areas where electrons are continuously accepted, leading to the reduction of the structure, and anodic areas where the oxidized metal dissolves, resulting in a corrosion current and the dissolution of the structure in question. Distinguishing between chemical and microbial corrosion is often difficult because the two processes enhance each other.

Although not a universal standard, the use of purple plastic (polyvinyl chloride, PVC) pipes for reclaimed water systems, originally introduced by California, is widely used. PVC and similar materials offer advantages over steel and concrete pipes since they are 30–70% less expensive, easy to install, non-corrosive, and durable with an expected design life of more than 100 years without the extensive and expensive corrosion treatments (Baird

2011). Galvanized steel or concrete purple pipe with attached purple tape or stenciling (CDEH 2001; COR 2012) is also becoming increasingly acceptable. Permissible sizes range between 2½ inches and 12 inches (6.35–30.48 cm) in diameter and conform to specific American Society for Testing and Materials and pressure requirements.

Distribution system infrastructure management

Valve management is an essential aspect of distribution system management. The overall reliability of a distribution system depends largely on having an adequate number of valves, as well as their location and reliability. Implementing a valve management program and adding valves to the system in strategic locations are ways to achieve system reliability (Deb *et al.* 2012). Management programs that include regular exercising and maintenance of valves are more cost-effective than the addition of new valves to an existing system. Deb *et al.* (2006) developed a strategic valve management model (SVMM) allowing the user to delineate segments, perform deterministic and probabilistic analyses, and calculate the performance indicators. In order for a utility to fully benefit from using the SVMM software, they should collect and maintain data on valve location, accessibility, exercising, operation, and replacement, then link these data with the utility's geographic information database. In the absence of SVMM software, utilities should consider the following aspects of valve management in developing a cost-effective valve management program (Deb *et al.* 2012):

- Provision of enough valves to satisfy the $n-1$ rule ($n-1$ valves at a junction of n pipes).
- Average pipe length per valve should be between 500 and 700 feet (i.e., 152–213 m).
- To isolate a break, the maximum number of valves to be closed should be four or fewer.
- Utilities should set a goal of exercising valves once every two to three years and annually for valves 16 inches (40.64 cm) or larger.
- Dedicated crews for valve maintenance and repairs should be considered. However, cross-training staff should be considered, particularly during emergency conditions.

Cross-connection control

Cross-connection is a link between two systems, notably the reclaimed water and the potable water system. However, there can also be a link between the reclaimed water and sewer system. Such linkages can compromise the quality of potable water or reclaimed water, threatening public health. A cross-connection control manual developed by the United States Environmental Protection Agency (USEPA) presents the methods and devices used for preventing backflow and back-siphonage (USEPA 2003). The USEPA manual describes and discusses the six basic types of devices that can be used to correct cross-connections: air gaps, barometric loops, vacuum breakers (both atmospheric and pressure type), double check with intermediate atmospheric vent, double check valve assemblies, and reduced pressure principle devices. The selection of the appropriate device is generally based upon the level of hazard posed by the cross-connection. Additional considerations are based upon piping size, location, and the potential need to test devices to ensure proper operation (USEPA 2003). Methods for instant detection of cross-connection incidents are still lacking but technologies such as fluorescence excitation–emission matrices are promising (Yan *et al.* 2000; Hambly *et al.* 2010). The technique develops fingerprints (spectra) for different water bodies based on salinity, humic acid, and protein content.

Hydraulic pressure

It is preferable that end-users have a reliable supply of reclaimed water. This practically requires the capability to provide adequate supply under both normal and abnormal conditions. One aspect of ensuring enough hydraulic pressure is the proper design of the distribution network with a combination of pipe diameters that meet layout, connectivity, and water demand (Daccache *et al.* 2010). In most instances, the design issues associated with pressure drops and pumping of reclaimed water have not been adequately addressed as most systems have traditionally handled water-using operations and water-treating operations as separate entities. Hung & Kim (2012) recently published an automated design method able to simultaneously calculate pressure drop and design water pumping in the context of a distribution network. Kirmeyer *et al*. (2000) presented some distribution system pressure requirements (Table 2) for potable water that may also be applicable for reclaimed water.

Models such as EPANET are useful in tracking water flow in pipes, pressure at each node, water height at each tank/reservoir, concentration of chemicals, and decay of the disinfectant in reclaimed water systems. It can also be used to simulate water age and water quality, model valve shutoff, as well as regulate and control pressure. EPANET is also capable of modeling pressure-dependent flow issuing from sprinkler heads (USEPA 2012a). It can be used to evaluate alternatives for improving water quality, modifying pumping regimens, locating disinfection booster stations to maintain target residuals, planning pipe cleaning and replacement as well as improving the overall system's hydraulic performance. More customized applications involving complex reaction schemes between multiple biological species (including biological regrowth) and chemicals in the bulk flow and pipe wall have been incorporated into an improved EPANET-Multi-Species eXtension (EPANET-MSX) (USEPA 2012a).

Joksimovic *et al*. (2008) published a decision support system for developing design principles for water reclamation systems. While the publication focused on designing the treatment train, it tangentially considered distribution system optimization with regard to pipe sizing, reliability, pumping stations, reservoirs, redundancy as well as future development and related changes in water demand. The software developed in that study permits evaluation of the distribution system by allowing users to specify the location of pumping, transmission and storage facilities and providing a least cost preliminary sizing that meets operational requirements. The software included a knowledge base, namely preliminary, primary, secondary, tertiary, and disinfection and control modules for evaluating treatment performance, distribution system sizing and system optimization. Of most relevance to the present review is the distribution system sizing module for locating pumping and storage facilities on a predetermined branched layout. This function is used to identify reclaimed water volumes transferred to each user, calculate the pipe head losses for optimal pipe sizes and pumping stations based on monthly flow rates, and size and cost the seasonal storage elements of the distribution network using maximum storage carryover arcs.

CUSTOMER RELATIONS AND SATISFACTION ISSUES

Table 3 summarizes the customer relations and perceptions issues identified by the survey. Sustaining reclaimed water production and usage requires satisfying customer requirements and product quality. Public perception on the use of reclaimed water as an alternative water supply has to be favorable. Perception and acceptance are negatively influenced especially when reclaimed water turbidity and color are objectionable (Rowe & Abdel-Magid 1995). Jjemba *et al*. (2010a) reported a high correlation between turbidity and apparent color in two systems with open ponds ($R^2 \geq 0.8$) which had significant algal growth than in two membrane bioreactor (MBR) systems ($R^2 \leq 0.6$).

Elevated levels of bacterial growth can result in a loss of oxygen and the creation of anoxic conditions resulting in odor. The odor is attributed to hydrogen sulfide and black water (iron sulfides) which give water a 'rotten egg' smell (Delgado *et al*. 1998). Odor can generate customer

Table 2 | Distribution system pressure requirements

Requirement	Value (psi)	Value (kPa)	Location	Sources
Minimum pressure	35	241	All points within distribution system	AWWA (1996)
	20	138	All ground level points	GLUM (1997)
Desired maximum	100	690	All points within distribution system	AWWA (1996)
Fire flow minimum	20	138	All points within distribution system	AWWA (1996)
Ideal range	35–60	241–414	All points within distribution system	GLUM (1997)

Table 3 | Customer relations and perception issues with reclaimed water

• Customer dissatisfaction with the water	• Lack of policing against watering day violations
• Public perception (sewer water) and acceptance	• Getting customers to convert to reclaimed water
• Misconceptions about availability of reclaimed water services (including demanding end users)	• Customers not utilizing reclaimed water to full capacity
• Satisfying customer demand in late summer vis-à-vis minimal winter demand	• Drought
• Educating customers about over-watering/watering days and restrictions	• Expanding uses for reclaimed water and associated widening of the customer base (e.g., getting industrial or cooling tower customers to use reclaimed water)
• A high variability in system (customer) demand	• Customer practices such as poor control of runoff from properties
• Customers not following the rules	

complaints (ACCB 2006). Its management is discussed in the section Water quality in reservoirs and distribution systems.

Irrigation is the most common usage of reclaimed water. Thus, its demand can be largely impacted by the prevailing season leading to rationing so as to meet client demand in some locations (Jjemba *et al.* 2010a). In terms of nutrients, reclaimed water is deemed superior to potable water for irrigation purposes. If the reclaimed water is to primarily be used for irrigation purposes, operators have to be mindful of nutrient levels. If excessive, nutrients can cause injury to the irrigated vegetation and also increase the possibility of contaminating the groundwater. Reclaimed water that is used for irrigation also has to be treated to minimize salinity, which can occur if the water contains high levels of sodium bicarbonates (Wu *et al.* 2008). Saline soils display a high electrical conductivity (namely, >4 mS/cm) which can negatively affect vegetation by lowering the free energy of water in the soil matrix and reducing the ability of the plant roots to extract moisture from the soil owing to the osmotic pressure generated by the electrical conductivity.

Most of the issues raised about customer relations and perception (Table 3) can be addressed through a multi-pronged approach that requires:

- putting reclaimed water into larger context of a water portfolio;
- maintaining constant communication with customers through open house activities, newsletters, webcasts and similar outreach activities;
- branding reclaimed water through advertising and highlighting the associated benefits and shortfall of its use (Davis undated);
- involving customers in the decision-making processes;
- developing partnerships at all possible levels;
- providing avenues for constant feedback to and from the customers.

Macpherson & Slovic (2011) developed several guidelines for engaging customers about reclaimed water issues.

WATER QUALITY IN RESERVOIRS AND DISTRIBUTION SYSTEMS

Within the USA, there are no federal regulations about reclaimed water use. Some states have their guidelines or regulations of varying scope (USEPA 2012b). Overall, the states have specific water quality standards regarding organic content (biochemical oxygen demand (BOD) or total organic carbon (TOC)), nitrogen, bacteria (particularly fecal coliform), and chlorine residuals in the effluent. Most of these requirements are focused on reclaimed water effluent. However, monitoring reclaimed water immediately after treatment does not provide a true representation of quality at the point of use. Reclaimed water has a shelf life whereby storage, age, and conveyance (i.e., packaging) cause deterioration in water quality, with aesthetic and public health implications. Deterioration of water quality during storage in reservoirs and the distribution network is a major challenge for the industry. The generic issues raised by the industry about reclaimed water quality are presented in Table 4.

In addition to microbial criteria for reclaimed water, some specific physical and chemical surrogates for microbiological water quality have also been identified. For example,

Table 4 | Generic water quality issues and problems identified

• Growth of algae and other aquatic organisms in reservoir	• Sulfide odors from irrigation systems operated biweekly
• High salinity/TDS/salts content/salt management and effects on plants	• Maintaining quality in reservoir
• Managing nutrient (ammonium, nitrate) levels	• Not enough nutrients to keep the grass green
• Poor quality at end of branched system	• Lack of information on water quality parameter requirements for discharge
• Inadequate chlorine residual	• Meeting the total coliform limits of <23 daily and <2.2 monthly
• Biofilm concerns	• Unclear water quality (requirements) for cooled water chillers and industrial cooling
• THM production in the system (due to chlorination requirements)	

total nitrogen concentrations ≤10 mg/L, turbidity ≤2 NTU, total suspended solids (TSS) ≤5 mg/L, BOD ≤45 mg/L, TOC ≤5 mg/L, carbonaceous BOD of 60 mg/day, and residual chlorine concentrations greater than 1 mg/L are reflective of high-quality effluents. A recent survey of 21 reclaimed water plants (activated sludge (AS) with secondary treatment as extended aeration, oxidation ditches, trickling filters, anaerobic/anoxic/oxic process, rotating biological contactor (RBC), MBR, or modified Ludzack–Ettinger process) showed a median TOC of 5.5 mg/L and median assimilable organic carbon (AOC) of 450 μg/L (Weinrich *et al.* 2010). Jjemba *et al.* (2010b) noted less frequent occurrence of common indicator organisms in two MBR systems, which also had lower carbon levels (Figure 2). The percent occurrence was based on 19–57 samples collected over four consecutive seasons (Table 5). However, no association between human pathogens (e.g., *Legionella* and *Mycobacterium*) and carbon levels was observed in these reclaimed waters.

Aesthetics and water quality are primary issues affecting consumer perceptions, permits, and water use choices (e.g., irrigation versus cooling towers, toilet flushing, etc.). A major driver for such deterioration is the loss of disinfectant residual. This section is therefore devoted to examining reclaimed water quality issues of aesthetic, physical, operational, and biological nature.

Algae and macroorganisms' management

Long retention times coupled with high nutrient loads typical of reclaimed water are ideal for intense algae growth in open reservoirs. Excessive nitrogen and phosphorus support photosynthesis and algal biomass accumulation, which is also influenced by climatic conditions, specifically sunlight and warm temperatures. Thus, most algal biomass is accumulated in summer and fall. Algal proliferation is not only limited to the reservoir but also impacts the distribution

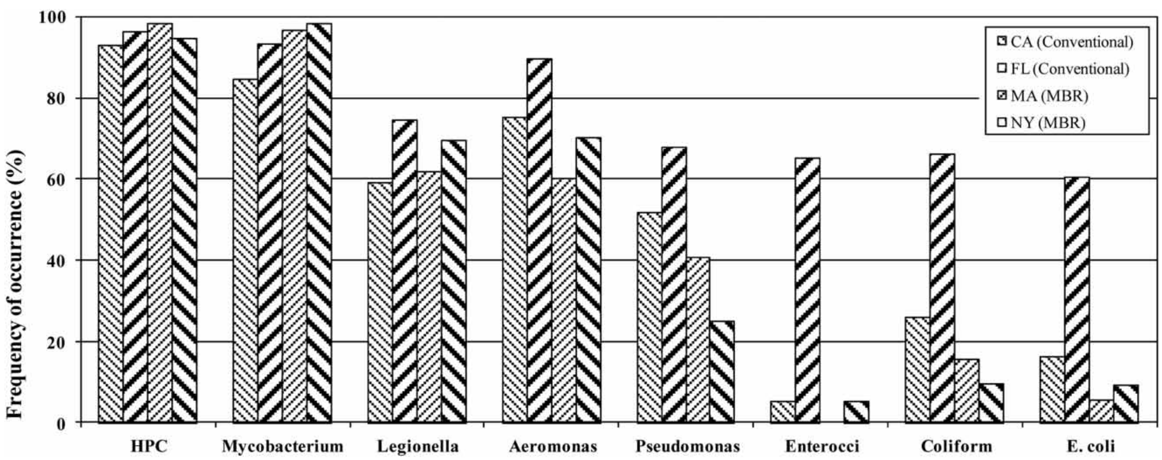

Figure 2 | Frequency of occurrence of opportunistic pathogens and indicator bacteria in reclaimed water (*Source:* Jjemba *et al.* 2010b).

Table 5 | Total number of samples analyzed

Organism	CA	FL	MA	NY
HPC	55	51	57	55
Mycobacterium sp.	51	41	56	56
Legionella sp.	56	51	55	56
Aeromonas sp.	20	19	20	20
Pseudomonas sp.	31	31	32	32
Enterococci	20	20	20	20
Coliforms	31	41	33	32
E. coli	56	53	57	55

system, clogging sprinkler heads and also generating objectionable odors due to the formation of hydrogen sulfide (Jjemba *et al.* 2010b). The hydrogen sulfide was several magnitudes higher in two conventional systems compared to MBRs. Water systems with as little as 1 μg of sulfide/L are corrosive (Miller & Mancl 1997). Rashash *et al.* (1996) found that odor type and intensity related to the number of algal cells and the life stage of the algae, with the younger less dense algal cultures producing less intense odors.

Algal growth results in severe operational (e.g., flow disruption, clogging of sprinklers, etc.) and water quality issues in reclaimed water distribution systems. Algal problems were the most common issue during the storage phase for 11 of the 12 water utilities covered in a recent study by Rimer & Miller (2012). Some utilities controlled algae using copper sulfate ($CuSO_4$) or Cutrine®-Plus. Dosages of 1–2 ppm (1.4–2.7 pounds $CuSO_4$ per acre foot) were recommended when water temperatures are above 15.6 °C (i.e., 60 °F; Haman 2011). Cutrine®-Plus had more efficacy than copper sulfate (Rodgers *et al.* 2010). It is a liquid copper-based formulation with ethanolamine chelating agents to prevent copper precipitation in water. If algicides are used when cell numbers are high (i.e., >5,000 cells/mL), the subsequent cell lysis can lead to high concentrations of toxins and odor compounds which are difficult to remove (Brooks *et al.* 2008). Potassium permanganate, which may be applied directly or indirectly (by coating reservoir walls) may also be used to control algae. For chemical control strategies users have to be mindful of the potential impact on non-target organisms.

Enhanced coagulation, scraping walls, ozoflotation, dissolved air floatation, and ultrasonication have also been used to control algae (Benoufella *et al.* 1994; Lee *et al.* 2002; Ahn *et al.* 2007). Ultrasonication was demonstrated by Lee *et al.* (2002) on algal blooms on 32-hectare Lake Senba in Japan using a set of prototypes (i.e., the Ultrasonic Irradiation System, USIS). Ahn *et al.* (2007) used ultrasonication in a 9,000-cubic meter eutrophic pond; whereas Klemencic *et al.* (2010) used a similar strategy in a fish pond. Ultrasonication destroyed the algal gas vacuoles, enhancing contact between the cyanobacteria and their lysing myxobacter, which in turn accelerated cell destruction. The ruptured cells sink in the reservoir.

The accumulation of algal cells can be controlled by using fine-mesh screens post-storage or regular flushing of the reclaimed water systems (Jjemba *et al.* 2010a). In a Sarasota distribution system, farmers used basket type filters (80–100 μ) at each irrigation pump station to control blockage from algae (Rimer & Miller 2012). Recently, American Water launched a water-energy nexus oriented project using floating solar modules on a reservoir (Figure 3). Arrangements like this in a reclaimed water open reservoir can minimize algal growth and maintain good water quality while providing other economic benefits (Anonymous 2012).

Reclaimed water may also be invaded by macroorganisms such as snails, worms (e.g., redworms), zebra mussels, turtles, fish, weeds (e.g., duckweed, moss, water hyacinth), and ferns (e.g., *Azolla*). Although chemical control is effective (Nelson *et al.* 2001; Turgut 2005), it may not always be the most desirable option. Biological control can be a viable alternative in some instances. For example, Tipping *et al.* (2008) reported good results with a weevil (*Cyrtobagous salviniae*) controlling a water fern (*Salvinia molesta*) in Texas and Louisiana (Figure 4). However, biological control agents have to be local as to avoid unintended consequences of trying to eliminate an invasive species with another invasive species. Table 6 summarizes some chemical and biological remedies for respective macroorganisms.

Microbial problems in distribution system

A summary of the common microbial problems associated with distribution systems and how they can be resolved is presented in Table 7. From an operational perspective, free

Figure 3 | Floating solar panels on a reservoir at Canal Brook WTP (Somerset, NJ).

Figure 4 | Documentation of the water fern (*Salvinia molesta*) infestation before and after release of a weevil (*Cyrtobagous salviniae*) at a reservoir in Louisiana (*Source:* Tipping *et al.* (2008), with permission from Elsevier).

chlorine disinfectant residual throughout the reclaimed water distribution system should at least be maintained at 0.2 mg/L (Narasimhan *et al.* 2005). Higher chlorine concentrations may be necessary depending on site-specific conditions. For example, utilities that do not provide nutrient removal may require higher residuals to prevent the growth of biofilm. For systems using free chlorine, a temporary switch to chloramine may be as effective in inactivating biofilm denizens (Flannery *et al.* 2006).

Biofilms

Most bacteria in water systems are attached to surfaces and piping material in intricate aggregate structures called biofilms (Lazarova & Manem 1995; MacDonald & Brözel 2000). Such aggregation of the cells increases the resistance to disinfection by several-fold (LeChevallier & Au 2002). Some of the cells slough off the biofilm and shed into the aquatic matrix (van der Wende *et al.* 1989) as a result of changes in flow rates, pH, nutrient status, disinfectant concentration, or disinfectant type. Based on Hausner *et al.* (2012), planktonic heterotrophic plate count (HPC) were strongly correlated with biofilm growth, suggesting that high planktonic cell counts can also be indicative of potential biofilm problems. In the study by Hausner *et al.* (2012), water age was not consistently correlated with biofilm growth metrics, suggesting that distribution models calibrated only for water age will not reliably diagnose biofilm-prone systems. By contrast, biofilm growth was highly correlated with total chlorine demand, suggesting

Table 6 | Control measures for various macroorganisms in reclaimed water

Macroorganism	Control chemical[a]	Biological control[b]
Snails and other molluscs	Chlorine at ≥3 mg/L; copper sulfate at 504 mg/L (Oplinger & Wagner 2009)	Cover with gas impermeable benthic barriers such as EPDM suffocates mussels (Wittmann *et al.* 2012)
Worms (Oligochaete)	Shock chloramination with 32 mg/L for 75 min (Broza *et al.* 1998); supechlorination	Reduced organic materials, e.g., through aeration as high oligochaete presence is an indicator for such contamination
Mussels and other bivalves	EarthTec® for at 17 mg/L (Watters *et al.* 2013), Bayer 73®, sodium hypochlorite (Kilgour & Baker 1994)	Cover with gas-impermeable benthic barriers such as EPDM suffocates mussels (Wittmann *et al.* 2012); predation by crayfish (*Pacifastacus leniusculus*; zu Ermgassen & Aldridge 2011), sparker pressure pulses application of 5.8 J/m^2 per pulse (Schaeffer *et al.* 2010)
Duckweed	Herbicide spray (e.g., metazachlor, diuron at 60 μg/L especially when combined with copper, linuron at 70 μg/L). Also reported was Aquathol® K; increase water to pH >8	Fungi (e.g., *Myrothecium roridum* in S. Korea)
Ferns	Herbicides (e.g., diquat, glyphosate); Increase water to pH 8 (only effective in early invasion)	Fungi, weevils (e.g., *Cyrtobagous salviniae* in TX and LA)
Moss	Increase water to pH > 8; fluoridone (low doses of 5–15 μg/L over a long duration work best; Getsinger *et al.* 2008)	No known biocontrol measure

[a]Pesticide, herbicide applications have to conform to USEPA guidelines. Their use should also be mindful of potential impact on non-target organisms including the irrigation fields.
[b]The biological control agent of choice should preferably be local (or certified by USDA/ARS) as to avoid unintended consequences of trying to eliminate an invasive species with another invasive species.

that models calibrated for chlorine demand can be used to identify areas of potential biofilm growth. Biofilm densities of *Mycobacterium avium* increased with increasing levels of AOC (Norton *et al.* 2004). A more diverse microbial population was documented on metallic than plastic surfaces (Norton & LeChevallier 2000) signifying complex but important relationships between pipe materials and biofilm proliferation (see Biofilm and corrosivity of materials section below).

Biofilm sampling and analysis

Biofilm growth can be evaluated on coupons of different pipe materials. Owing to the complexity of microbial communities and diverse materials found in water distribution systems, several methods are used to assess biofilm development.

- Detection of viable microorganisms able to replicate under test conditions.
- Direct counting of microorganisms using microscopy (e.g., fluorescence, confocal laser scanning microscopy, flow cytometry, etc.).
- Biochemical assay methods such as adenosine triphosphate (ATP) (Evans *et al.* 2013).

However, Hausner *et al.* (2012) reported limited capability from flow cytometry for biofilms in water systems due to interferences associated with common pipe materials, such as particulate debris from cast iron and cement. The assay for ATP on surfaces (including coupons) as a surrogate for biofilm formation has a very short turnaround time that is absolutely ideal for water distribution systems (e.g., www.waterandwastetesting.com).

Biofilm and corrosivity of materials

Corrosion and bacterial growth are confounded and can influence each other. Thus, several studies have compared biofilm growth on various pipe materials and found corrosion as a significant factor in biofilm formation. Materials such as unlined cast or ductile iron pipe have shown the greatest biofilm accumulation whereas materials such as PVC have shown the least accumulation and related corrosion (Camper 1996). On the contrary, Cloete *et al.* (2003) reported higher biofilm formation on PVC than

Table 7 | Common microbial problems and potential solutions

Problem	Potential cause	Mitigation alternatives
High bacterial levels at point of entry	• Inadequate treatment	• Treatment assessment and optimization
	• Insufficient disinfection	• Increase disinfectant application
	• Intrusion	• Infrastructure inspections and improvements
High bacterial levels in distribution pipes	• Insufficient residual maintenance	• Provide booster disinfection or increase residual at existing booster stations
	• Biofilm growth and sloughing: sediment accumulation	• Decrease system residence time
	• Intrusion	• Loop versus branch system design
		• Biofilm control: flush and disinfect distribution mains, or occasional use of chloramine disinfectant
		• Infrastructure inspections and improvements
Poor microbial quality in storage facilities	• Inadequate turnover	• Decrease detention time
	• Sediment or biofilm accumulation	• Reconfigure inlet/outlet piping
	• Algae growth in open reservoir	• Install internal baffling
		• Inspect and clean storage facilities
		• Cover reservoir, if feasible
		• Algicide application (e.g., Cutrine®-Plus)
		• Post-storage strainers/filters
		• Nutrient removal at treatment plant
		• Watershed control
Clogged sprinkler heads at point of use	• High bacterial levels in distribution system	• See above
	• Stagnation in service connection	• Increase frequency of flushing of service connection

galvanized pipe surfaces, whereas Pedersen (1990), Zacheus *et al.* (2000), Wingender & Flemming (2004), as well as Lehtola *et al.* (2005) did not detect any differences in biofilm formation between PVC, stainless steel, and polyethylene (PE). Similarly, Manuel *et al.* (2007) did not detect differences in biofilm development on PVC, cross-linked PE, high-density PE, and polypropylene in three types of reactors. These seemingly conflicting results may be explained by the relatively new biofilms used for some of the studies. The more stable laboratory conditions in which some of these studies were conducted as opposed to what happens in real distribution systems which are impacted by temperature extremes, nutrient fluxes contributed by the pipe surface composition, as well as hydrodynamic conditions may also have contributed to the contradictory results. From a remedial perspective, copper pipes required a higher chlorine dose than plastic pipes to effectively disinfect biofilms (Lehtola *et al.* 2005).

Disinfectants and water quality

Disinfection is intended to manage the risk of waterborne disease transmission. In the USA, chlorine and chloramines are commonly used disinfectants. Both react with many trace compounds within the bulk water, natural organic matter and the pipe wall material, leading to a loss in disinfectant residual (Vasconcelos *et al.* 1996; Valentine *et al.* 1997). Several other factors including the disinfectant to nitrogen ratio, pH, disinfectant dose, temperature, inorganics, and organic carbon contribute to disinfectant decay (Jafvert & Valentine 1992; Lieu *et al.* 1993; Valentine *et al.* 1997). During decay, disinfection by-products (DBPs) are also formed. In general, increasing the chlorine to nitrogen ratio inhibits nitrification but increases the formation of DBPs. Inorganics such as ferrous (Fe^{2+}), copper (Cu^{2+}), and manganese (Mn^{2+}) also consume chlorine disinfectant, becoming themselves oxidized in the process (Nguyen *et al.* 2011). Dissipation of the disinfectant leaves water vulnerable to the regrowth of bacteria and proliferation of biofilms as well as contamination from system breaches and intruding contaminants (Jjemba *et al.* 2010a, 2010b). Thus, managing disinfectant loss in distribution systems also has to manage the potential impact of these setbacks.

Using a booster disinfection station physically separates the disinfection doses, with multiple delivery coordinated doses applied throughout the distribution system (Tryby *et al.* 1999). This approach separates the microbial inactivation (disinfection efficiency) requirements of the effluent from the need to maintain disinfectant residual in the distribution system. Thus, a booster disinfection management style introduces flexibility in the operations of the reclaimed water plant and distribution system as network usage characteristics change over time. The strategy enables matching the dose to the unique residence time of the water parcel, reducing disinfectant use and its associated DBPs.

Linear superposition in a booster disinfection design and analysis (BDDA) software was developed to optimize the effects of multiple booster dosages and station performance (Uber *et al.* 2003). For the same system, the introduction of four booster stations reduced the amounts of chlorine used by 50%, compared to the conventional approach. Boosters also had the added advantage of a better redistribution of the disinfectant from the treatment plant into the distribution system; resulting in a more uniform (less variable) residual throughout the distribution system (Figure 5). It should be noted that booster chlorination still requires disinfection at the treatment plant, while still relying on disinfection within the distribution system to maintain adequate residuals. Despite the potential improvements in maintaining residuals using BDDA software, there is no evidence that reclaimed water utilities are using such resources for guiding decisions on locating booster stations.

Influence of pH

The efficacy of chlorine disinfection is dependent on pH. At a pH less than 7.5, HOCl is the predominant species whereas at higher pH levels, the less efficacious OCl^- is the predominant species. Results from two reclaimed water systems on consecutive days showed predictable pH increases in the storage and distribution systems compared to the effluent (Figure 6). The increase can negatively impact the efficacy of a residual disinfectant in the

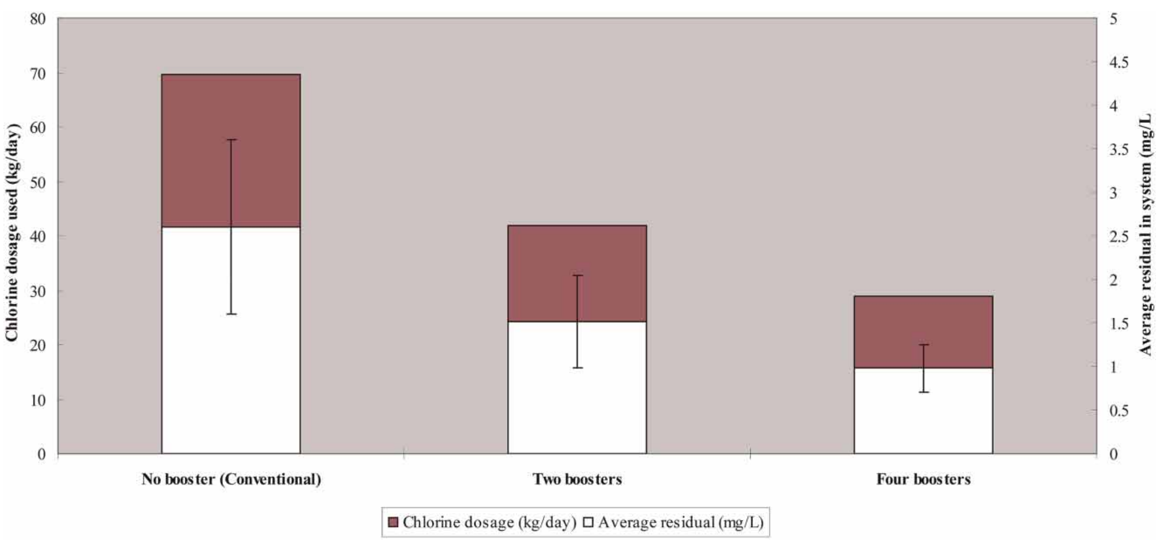

Figure 5 | Differences in the amount of chlorine used and residual levels in the system after adding two and four booster stations. Error bars represent the standard deviation of chlorine residuals (figure based on data from Uber *et al.* (2003)).

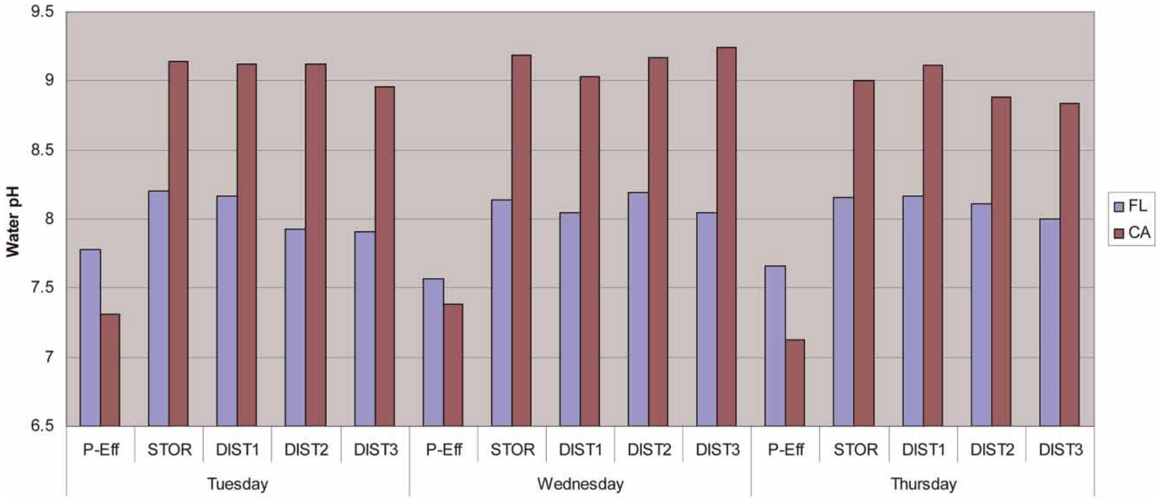

Figure 6 | The pH of reclaimed water from two conventional facilities in summer 2007. For each facility, the water was sampled from the effluent, storage, and three points within the distribution system (Jjemba *et al*. unpublished).

distribution system. For example, White (1992) showed much lower disinfection efficacy at pH 9 possibly because of predominance of the less efficacious OCl^- moiety. A slight increase in chlorine decay with increasing pH was reported by Fleischacker & Randtke (1983). Changes in pH also affect the stability of chloramines. For example, between pH 6 and 8, decreasing the pH increased the decay of monochloramines due to the formation of dichloramine (Jafvert & Valentine 1992). Collectively, these observations have implications as the water pH in the system at the point where a booster disinfectant is applied can impact disinfection efficacy.

Infrastructure effects on disinfectant efficacy

The type of pipe wall has an impact on disinfectant decay. For chlorine, decay increases with PE, PVC, epoxy, cement, and iron pipes in that order whereby PE is least reactive and iron is most reactive (Brandt *et al*. 2004). The rate of decay of chloramine is comparatively lower than chlorine decay. The difference in rates of decay between chloramines and chlorine is estimated at a factor of ten (Brandt *et al*. 2004). At this point, it is not clear what fraction of reclaimed water plants chlorinate to breakpoint as opposed to those which use chloramine.

The rate of disinfectant decay is inversely proportional to the pipe diameter. This is inherently assumed in the EPANET decay model (USEPA 2012a). Furthermore, high water velocity may disturb sediments which in turn increases their reaction with chlorine. It may also increase the rate at which chlorine transfers to the pipe wall. It is not clear as to what proportion of the reclaimed water utilities use EPANET in guiding their disinfection or modeling their hydraulic and water quality behavior of water in reclaimed water distribution piping systems.

Disinfection by-products

Relatively high levels of chlorine (i.e., 5–20 mg/L) can be applied to ensure adequate disinfection of viruses and other pathogens prior to use of reclaimed water. However, these levels can cause formation of nitrosodimethylamine (NDMA) and other DBPs. DBPs may be of greater concern in drinking water compared to reclaimed water, except where reclaimed water is for indirect potable reuse (e.g., aquifer recharge). There are no guidelines on the levels of NDMA in reclaimed water used for irrigation or landscaping.

Pehlivanoglu-Mantas *et al*. (2006) displayed unique characteristics to NDMA formation in relation to the disinfectant residual and concentrations (Figure 7). Whereas systems A, B, and C had been disinfected with chloramines (NH_2Cl), D, and E had been disinfected with chlorine ($HOCl/OCl^-$). Low (4 ng/L) residual levels in A resulted in

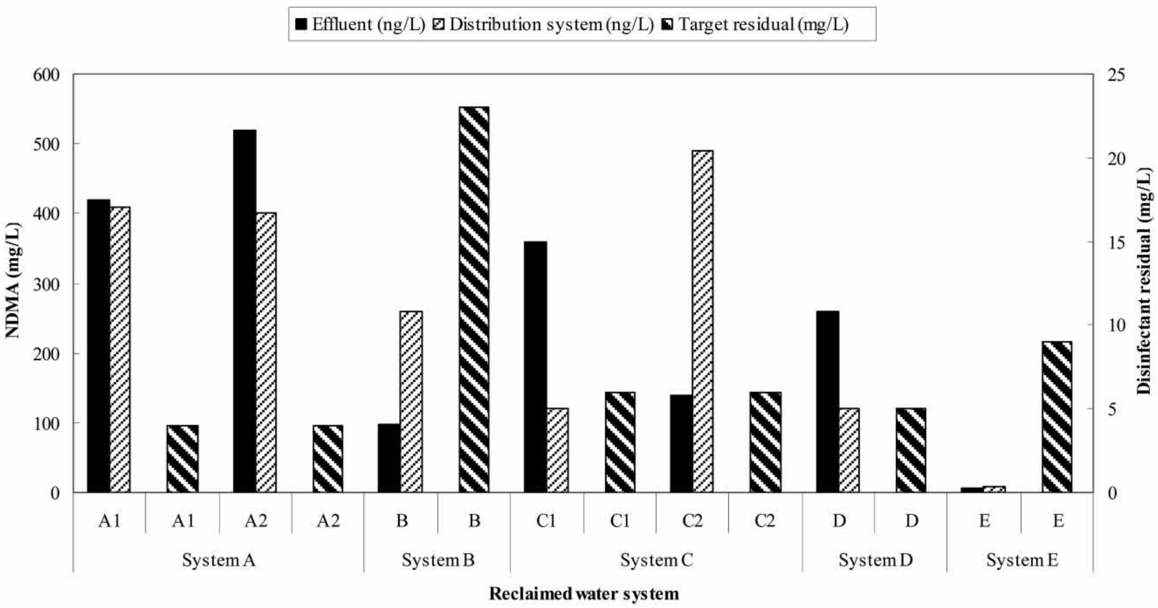

Figure 7 | NDMA formation in reclaimed water containing different levels of chlorine residuals. The numbers following each letter indicate sampling of the same system on different days (figure based on data from Pehlivanoglu-Mantas *et al.* (2006)).

high NDMA concentrations in the effluent and distribution system. By comparison similarly low levels of chloramines-based residuals in system C resulted in a low NDMA concentration in the effluent but these NDMA concentrations were subsequently elevated in the distribution system. System B, which had also been disinfected with chloramines but at a high target residual concentration of 23 mg/L, also initially had NDMA concentration of 97 ng/L which increased by 168% in the distribution system. With chlorine as the disinfectant, systems D and E target residuals of 5 and 9 mg/L, respectively. System D inherently generated a higher level of NDMA compared to system E despite the higher disinfectant residuals in E. Overall, systems with excess ammonia which had been disinfected with chloramines led to the formation of 120–460 ng NDMA/L in the distribution system.

The discussion above shows that the drivers for NDMA formation in water are still not clearly understood. Control is possibly best attained by use of alternative disinfectants than chlorine or chloramine. For example, ultraviolet light (UV) radiation decreased NDMA levels, with 40% removal at a dose of 100 mJ/cm², whereas free chlorine did not significantly change NDMA levels (Tang *et al.* 2010). Of the 43 trace organic compounds analyzed during the pilot tests, 24 were consistently detected in the fully nitrified filtered effluent. Results with combined UV/free chlorine doses were consistent with those predicted from the individual doses. Similarly, trihalomethanes (THMs) were not detected after UV treatment (Tang *et al.* 2010).

Retention time in the reservoir and distribution system

Studies by Brandt *et al.* (2004) attributed water quality in the distribution system to (i) the quality of the treated water supplied into the network, (ii) condition of distribution assets within the network, and (iii) retention time within the network. The importance of retention time of water in the reservoir and distribution system on water quality cannot be emphasized enough. Impacts of storage-associated water quality problems are summarized in Table 8. Managing acceptable retention time with or without hydraulic models will in turn address these problems. Other considerations for managing this important parameter include altering valves in the network, installing time varying valves, flushing, downsizing the mains (see Minimizing retention in pipes section below), adjusting pump schedules, altering reservoir configuration, and altering distribution system configuration.

Table 8 | Reclaimed water quality problems associated with retention time

Problem	Parameter to measure	Potential causes	Impacted area(s)
Regrowth	• Bacteria (e.g., coliforms, HPC, *Legionella*, etc.)	• Reduced residual disinfectant	Reservoir and pipes
		• Intrusion	
Algal and cyanobacteria growth	• Chlorophyll	• Excessive nutrients in presence of sunlight	Open reservoir and pipes
Loss of disinfectant	• Chlorine	• Matrix demand	Open reservoir and pipes
	• Chloramine	• Wall demand	
		• Dissipation	
Nitrification	• Nitrite	• Microbial activity	Open reservoir and pipes
	• Ammonia	• High organic content	
	• DO	• Low DO	
Discoloration	• Metals (e.g., iron, manganese, copper)	• Pipe corrosion	Reservoir and pipes
	• Turbidity	• Sediment accumulation	
	• Color	• pH changes	
	• pH		
Odor	• Hydrogen sulfide	• Anaerobic conditions	Pipes
	• Mercaptans	• Diminished disinfectant	
	• Phenolics	• Algal cell accumulation and death	

Retention time is controlled by the physical characteristics of the system and the operation regimen. Physical characteristics include the pipe roughness, pipe size, frequency of dead-ends, pipe slope, and leakages. Operational regimes may be structured (e.g., pumping schedule) or uncontrolled as is the case for response action to meet demand needs. Brandt *et al.* (2004) focused on retention time in potable water distribution systems but some of the principles (i.e., parameters influenced by retention time; analysis tools and methodologies for determining retention time; water quality issues associated with retention time): and practices (i.e., operational and engineering solutions for reducing retention times) identified in their study may apply to reclaimed water systems as well.

Several strategies for managing retention time are presented in Table 9. However, most of these practices are implemented by utilities without necessarily classifying them as retention time management techniques but rather as water quality improvement measures. Some of the practices are adapted to solve a specific water quality problem (reactive) rather than proactively during the day-to-day operation of the network. Most widely used by water systems to minimize retention time is flushing of pipe networks. However, as noted in a recent survey, flushing is not always accepted for reclaimed water distributions systems (Jjemba *et al.* 2010a). A recommendation to flush the reclaimed water back into the sewer has been suggested. Altering the valving of the network (manually or using an automated system) is also used to control water retention time in localized parts of the distribution system. Retention time can be reduced by minimizing the number of shut valves required to produce hydraulic boundaries. Alternatively, shutting valves can reroute the water through part of the system with high demand.

Minimizing retention in pipes

Retention of reclaimed water can be enhanced by increasing the piping efficiency ratio (PER) achieved through a declining pipe system diameter design. The declining diameter provides unidirectional velocities with a critical scouring

Table 9 | Practices for controlling water retention time[a]

Method/Practice	Details	Remarks
Altering valves in the network	Travel times and water rerouting as to maximize flow velocities implemented by changing valve arrangements and hydraulic boundaries	Applied in response to a specific problem (i.e., reactive) as opposed to proactively managing retention time and water age
Installing time varying valves	Control valves timed to control the flow	Increases efficiency as physical monitoring and operation are not required. This cuts down on labor costs
Flushing	To remove sediments, biofilms, and reduce water age in dead ends and low flow sections of the distribution system. It can be manual (e.g., based on a flushing timetable) or automatically triggered by an event (or timer)	Flushing of reclaimed water systems is currently not permitted in some jurisdictions (Jjemba *et al.* 2010a)
Downsizing mains	Reduce system capacity to increase water velocities	For potable water, engineering design standards require specific pipe sizes for specific parts of the system (i.e., standard minimum size pipes to meet peak diurnal and seasonal demands for drinking and fire flows; Twort *et al.* 2000). It is not clear whether similar standards for reclaimed water systems exist or whether those for potable water are the ones directly adapted for reclaimed water
Increase turnover in the reservoir	Reducing strategic storage and managing diurnal storage depending on pump capacity and other resources	May not always be possible as, depending on end use, reclaimed water needs can be seasonal
Reducing the top water level of the reservoir	Reducing the strategic storage level based on the season	Especially in open reservoirs where algal growth can be a issue
Adjusting pump schedules	Optimizing pumping regimes to match supply and demand and minimizing energy requirements	Can be linked to increasing the rate of turnover in the reservoir
Altering the reservoir configuration	Install baffles to avoid dead zones	Applied in response to a specific problem (i.e., reactive) as opposed to proactively managing retention time and water age
Altering the distribution system configuration	Redesign certain sections as to avoid dead zones	Applied in response to a specific problem (i.e., reactive) as opposed to proactively managing retention time and water age

[a]Table modified from Brandt *et al.* (2004).

velocity flow, resuspending the particles (Slaats *et al.* 2002; Brandt *et al.* 2004; Buchberger *et al.* 2008). Pipe size optimization in the distribution system is an area of active research as it minimizes capital expenditure, reduce operating costs, and helps in maintaining adequate hydraulic pressure (Lamaddalena *et al.* 2012). For example, Zhang (2004) used PER (PER; i.e., the piping length to flow rate) to model reclaimed water distribution decisions. PER values of 2–378 were recorded (Figure 8). The smaller the ratio, the more economically suitable the potential reclaimed water supply, reflecting the economies of scale for the investment.

Odor control

Odorous compounds are formed slowly. Thus, retention time can indirectly impact their presence. Solving odor problems in reclaimed water storage and distribution systems should begin by investigating the following:

- How the systems or reservoir was designed.
- Whether operation of the systems or reservoir has changed.
- Whether odors are apparent on certain days or at certain times and not others.

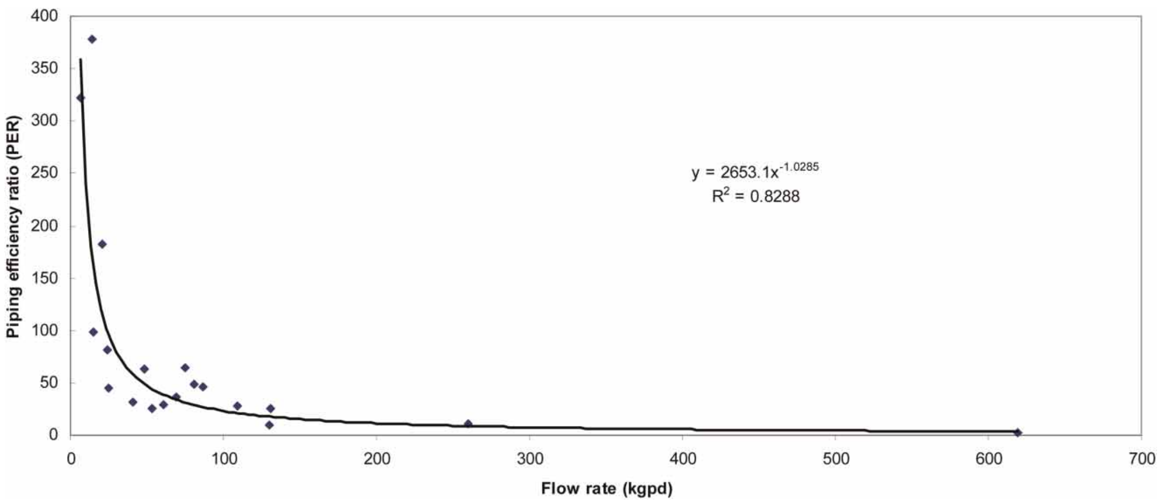

Figure 8 | Relationship between water flow rates and the PER (figure based on data provided by Zhang (2004)).

- Whether any part of the system or reservoir has been closed or added.

Understanding these questions may provide some clues to solving odor problems. In most instances, the odor is attributable to sulfur and sulfur-containing compounds. Sulfur is an essential component of organic materials present in proteins and some enzymes. Under aerobic conditions, it is decomposed to odorless sulfates. Under anaerobic conditions, however, it is converted to sulfides, notably hydrogen sulfide, mercaptans, and thiols. These gaseous compounds are toxic and corrosive at relatively low concentrations. For example, H_2S may be oxidized to sulfuric acid (H_2SO_4) on the moist surface of the pipe exacerbating corrosion problems (Islander *et al.* 1991). From a management perspective, anaerobic reduction of sulfate does not take place if dissolved oxygen (DO) or another more thermodynamically favored electron acceptor, e.g., nitrate, is present in water. Thus, aeration to more than 5 mg DO/L can significantly minimize H_2S formation (Rimer & Miller 2012). Mechanical aeration can be provided by a system such as SolarBee® (Bleth 2012). Other factors affecting the rate of H_2S generation include pH, temperature, nutrients, organic matter content, time of contact, presence of biofilm on the pipe surface, absence of sulfate reduction inhibitors, and the oxidation–reduction potential. Sulfide formation in reclaimed water increased rapidly at -140 to -211 mV but was diminished above -100 mV (Elmaleh *et al.* 1998).

Water discoloration

Discoloration of reclaimed water can be caused by a number of processes. Most notable is the growth of algae and cyanobacteria, giving the water a greenish color. It can also develop a reddish color due to iron (Fe^{3+}) oxides or a blackish coloration due to manganese (Mn^{4+}) oxides. Increasing pH from 7 to 9 decreases the release of iron. In some instances, coloration is enhanced by stagnation and the associated corrosion.

Salinity

As highlighted in the section Customer relations and satisfaction issues, salinity is a serious problem in reclaimed water. Salinity can damage crops and landscape vegetation (Camberato 2001; Fipps 2003). Plant damage occurs because of the high chloride and bromide concentrations or indirectly by forming sodic soils. Most tree crops (e.g., avocados), vine crops (grapes, pistachios, and pomegranates), and vegetables (e.g., beans, potatoes, spinach, strawberries, squash, and turnips) cannot withstand high total dissolved salts (TDS). By contrast, some crops such as barley, cotton, and Bermuda grass are tolerant to salinity. High TDS can also corrode pipes, cooling towers, and other structures. For cooling towers, TDS levels, together with nutrients such as phosphates, affect the cycles of concentration (COC). As TDS increases, the COC decrease (see the section Metals and nutrients). A major source of these salts is from the human dietary intake, gray water (through detergents), self-regenerating water softeners, swimming pools, as well as industrial and commercial discharges. Salts may also be added during the treatment system (e.g., addition of lime). Based on data from FWI (2012), the relationship between TDS and electrical conductivity in water is represented by Equation (1); whereby x = conductivity (μS/cm) and y is the TDS (mg $CaCO_3$/L):

$$y = 0.5x + (7 \times 10^{-5});\ R^2 = 1 \quad (1)$$

In a survey of 85 reclaimed water utilities, only 25% identified TDS as one of the constraints for use of reclaimed water (Thompson *et al.* 2006). A majority had no plans to implement best management practices to limit salinity, 25% had been or were considering such measures whereas 28% were not sure. Those findings are not entirely surprising because salinity is not associated with public health and is not included in most of the regulatory guidelines for reclaimed water. TDS levels >500 mg/L are representative of salinity conditions under the USEPA's secondary maximum contaminant level guidelines (USEPA 2012c). These guidelines are voluntary and only used to assist water systems in managing aesthetic considerations such as color and odor. Reclaimed water for the surveyed utilities was primarily for golf course irrigation (61%), landscape irrigation (35%), agricultural irrigation (28%), and industrial use (11%) (Thompson *et al.* 2006). In a follow up detailed survey, effluent average TDS levels were 768 mg/L.

Typical TDS levels for reclaimed water from various parts of the world are summarized in Table 10. High TDS can cause scaling in water pipes, boilers, and heat exchangers, restricting or even blocking water flow. When used for irrigation, high TDS water imparts osmotic stress, reduced soil permeability, and direct toxicity from specific ions (Tschobanoglous 1994). Thus high TDS affects crop yields but from an infrastructure perspective it also corrodes pipes and other structures. High TDS levels may also contain toxic ions that affect biotic communities (Marshall & Bailey 2004).

Various ways to manage salinity include source control, blending, brine line, reverse osmosis (RO), electrodialysis, and avoiding the use of rock salt and potassium chloride-based softeners. Alternatively, patrons should be encouraged to use portable-exchange softeners instead of self-regenerating softeners. Electrodialysis is whereby an electrical potential attracts dissolved ions through ion exchange membranes that are impermeable to water (Burbano & Brandhuber 2012). However, electrodialysis can be energy intensive; Veerapaneni *et al.* (undated) presented a linear relationship with the required energy (i.e., $y = 0.004x + 2.432$; $R^2 = 0.977$ where y is the electrodialyis energy required in kWh/1,000 gallons and x is the TDS in mg/L). Based on their estimate, reclaimed water of TDS 1,000–5,000 mg/L consumes 20–40 kWh/1,000 gallons. Thompson *et al.* (2006) combined the Economic Model and the Water Quality Analyst software program to understand contributors to salinity as well as the options for mitigating salinity in reclaimed water. The developed tool was used to consider the total TDS removed versus the associated cost. RO is preceded by low pressure membranes to remove large particles and foulants. The rejected waste is disposed, crystallized, or evaporated.

Metals and nutrients

The occurrence of higher levels of heavy metals in reclaimed water compared to potable water has been reported (Sacks & Bernstein 2011). Pereira *et al.* (2011) reported cumulatively higher concentrations of B and Cu on citrus groves irrigated with reclaimed water compared to those irrigated with well water. Similar incidences of high B and Cu were reported in soils and lemon leaves irrigated with secondary treatment effluents (Pedrero *et al.* 2012). However, long-term effects and yield differentials can greatly differ from one type of crops to another (Pereira *et al.* 2012).

Metals such as magnesium and calcium salts can precipitate in the reservoir and distribution system, especially where higher than pH 7.94 is maintained (Pedrero & Alarcón 2009). The accumulated metals can clog irrigation systems. This problem can be remedied by adding acid (e.g., HCl, phosphoric or sulfuric) continuously into the water system (Haman 2011). Such acidification can also remove existing scale buildup within the distribution system.

The corrosive nature of reclaimed water due to high concentrations of nutrients (e.g., organic matter, orthophosphate, TDS, and ammonia) has to be controlled for successful cooling recirculating systems. The nutrients also

Table 10 | Typical TDS values in reclaimed water

Location	TDS (mg/L)	Conductivity (μs/cm)	Source or type of water	End use	Reference
Cartagena (Spain)	1,589 ± 362	2.82 ± 0.26	Secondary effluent	Irrigation	Pedrero & Alarcón (2009)
Campotejar (Spain)	945 ± 54	2.10 ± 0.10	Tertiary effluent	Irrigation	Pedrero & Alarcón (2009)
Yanhu Al Sinayah (Saudi Arabia)	3,054	Not reported	Industrial WWTP	Industrial equipment cleaning; cooling; firefighting	Ahmad *et al.* (2010)
Yanhu Al Sinayah (Saudi Arabia)	1,081	Not reported	Sewage treatment plant effluent	Landscape irrigation	Ahmad *et al.* (2010)
Wadi Shueib (Jordan Valley, Jordan)	1,843 (range 324.9–7312.9)[a]	2,905 (range 798–8,310; $n = 365$)	Groundwater recharge	Irrigation	Kuisi *et al.* (2008)
El-Salaam Canal (Egypt)	Range of 291–2,556 depending on the season and location downstream	Range of 630–3,300 μmhos depending on the season and location downstream	Sampled at seven different locations; each sampling point receiving a fresh inflow of effluent	Irrigation	Hafez *et al.* (2008)
Ocotillo Electric Generating Station (Tempe, Arizona)	1,725	1,149	Reclaimed water from power plant (electric blow down cooling process)	Irrigation and groundwater recharge	Glenn *et al.* (1998)
Imperial Valley (California)	Range of 3,000–15,000	Not reported	Agricultural wastewater	Irrigation and surface water recharge	Kharaka *et al.* (2003)
Las Vegas Valley (Nevada)	1,650	Not reported	Return flow from treated wastewater effluent	Surface water recharge	Venkatesan *et al.* (2011)

[a]Values calculated from the provided anion and cation data as TDS is equal to the sum of cations and anions.

promote microbial growth, enhancing microbiologically influenced corrosion (biofouling). Corrosion can be minimized with inhibitors such as orthophosphate (Schneider *et al.* 2007). Other inhibitors are presented in Table 11.

Effects of nutrients on cooling towers

With cooling towers, the COC are very important, representing the concentration factor for the water in evaporative cooling systems. For example, COC5 implies that recirculating cooling water has five times the total dissolved solids concentration compared to makeup water. The Electric Power Research Institute provided chemical constituent guidelines for water used in cooling towers. These in mg/L include: Ca (300), $Ca \times SO_4$ (500,000), $Mg \times SiO_2$ (35,000), SiO_2 (150), total Fe (<0.5), Mn (<0.5), Cu (<0.1), Al (<1), S (5), NH_3 (<2), M alkalinity (30–50), pH (6.8–7.2), TDS (2,500), and TSS (100–150) (EPRI 2003). The pH and M alkalinity are applicable in the absence of corrosion inhibitors. If phosphate is present, the circulating water has to be strictly maintained between pH 6.8 and 7.2 to avoid formation of tricalcium phosphate [$Ca_3(PO_4)_2$], a very persistent scale.

To predict cooling tower water quality, EPRI developed WinSEQUIL software to address the complexity of cooling system chemistry. The software helps users identify operating scenarios likely to result into scaling from source water by preventing precipitation of ionic moieties due to increased solubility, allowing higher COC. A search of Google and

Table 11 | Corrosion and scaling control agents

Corrosion/Scaling	Category	Agents
Corrosion control	Inorganic-anodic	Chromate, nitrite, nitrate, molybdate, orthophosphate, and silicates
	Inorganic-cathodic	Zinc and polyphosphate
	Organic inhibitors	Azoles, amines and fatty polyamines
Scaling and fouling control	Chelant	Glucoheptonates
	Traditional inhibitors	Amines and fatty polyamines, phosphonates, phosphate esters
	Polymer	Polycarboxylic acid, polyacrylates, and polymaleic acid
	Natural dispersants	Ligno-sulfonates and tannins

Source: Dzombak (2011).

Web of Science did not show any significant usage of this program by reclaimed water plants or power plants possibly because its full utilization requires an understanding of reaction chemistry and multi-phase equilibrium relationships. The situation is remedied with makeup potable water and treatment with chemicals (Hsieh *et al.* 2010; Li *et al.* 2011).

OPERATIONAL ISSUES

Operation in this instance refers to the systematic design, direction, and control of processes that transform wastewater into reclaimed water and the processes to deliver the reclaimed water to its intended use. Working under the assumption that reclaimed water effluents meet quality regulations, this paper focuses on operational challenges to ensure maintaining such quality to the point of use. In this regard, the storage and conveyance of reclaimed water become very critical for handling a perishable product. However, upstream processes are crucial to the quality of water downstream and are important to manage through operations. The operational issues pertinent water treatment, preservation, and distribution identified through the survey are presented in Table 12.

Upstream treatment

Organic carbon greatly impacts reclaimed water quality, influencing color, turbidity, and regrowth of microorganisms. The most labile form of organic carbon, AOC is a good indicator of the propensity for microorganisms to proliferate in reclaimed water (Jjemba *et al.* 2010b). Weinrich *et al.* (2010) reported considerable variability in reclaimed water effluent quality for AS, sequencing batch reactor (SBR), and RBC (Figure 9). Some AS and SBR systems provided effluents of equal quality with the highly favored MBR systems. Those results strongly suggested the tremendous operational differences between plants. It is imperative to understand these management practices.

Reservoir design and management

Proper storage minimizes regrowth of microorganisms in reclaimed water (Gauthier *et al.* 2000). Product integrity in the reservoir can depend on the physical design of the

Table 12 | Generic operational issues and problems identified

• Handling solids	• Concerns about how numeric nutrient criteria may affect treatment requirements
• Maintaining chlorine residual in the distribution system	• Managing reclaimed water supplies during the dry season when demand is greatest
• Adequate storage of rechlorination tablets	• Dealing with high flows (including stormwater for combined flow systems) and/or reduced flow volume due to water conservation
• Coordination with wastewater utility (supplier)	• Lack of clarity on who should maintain the system (i.e., sewer or water)
• Wet weather disposal	• Variability in treatment operations that is centered on disinfection variables
• Setting pump to operating levels that turn over the tank more frequently	• Down time due to increased backwash frequency in summer months
• Debris in distribution system and clogging of irrigation heads and meters	

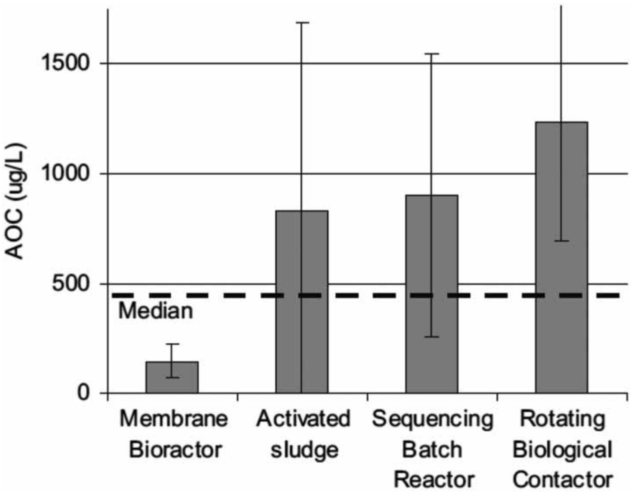

Figure 9 | Average AOC in effluents from MBR ($n = 3$), AS ($n = 12$), SBR ($n = 4$), and RBC ($n = 2$). Error bars represent the standard deviation of AOC for each treatment type (*Source:* Weinrich *et al.* 2010).

reservoir and how it is operated. Grayman (2000) evaluated the deterioration of water quality in the reservoirs. Possible causes of water deterioration under these circumstances include the following:

- Loss of disinfectant residual
- Odor production
- Leaching from linings
- Biofilm development on surfaces
- Sedimentation

Some of the design recommendations achieve good mixing through either complete mixing or a plug flow. The latter generally loses more disinfectant than the former. The difference in disinfectant loss between the two regimes grows with increasing disinfectant reactivity, increasing ratio of withdrawal time to filling time, and decreasing ratio of maximum to minimum water level. Thus, by default, good mixing reservoirs lose disinfectant at a lower rate than plug flow systems.

Baffling versus mixing

Internal baffles are mounted in reservoirs to direct and control the flow. However, in reservoirs, where mixed flow is preferable to plug flow, introduction of baffles inhibits mixing and can produce stagnant zones. Thus, baffling should, under most circumstances, be avoided in distribution system reservoirs. Water in distribution reservoirs should instead be mixed through the development of a turbulent (as opposed to a laminar) jet. To minimize energy requirements for such mixing, the inlet jet should not be pointed directly toward nearby impediments such as a wall, the reservoir bottom, or deflectors.

Stratification

Stratification can be a major problem in reservoirs and conditions that promote it should be avoided. Whenever there is a temperature difference between the contents of a reservoir and its inflow, the potential for poor mixing and stratification exists. Positive buoyancy, whereby temperature of the inflow is higher than ambient water temperature, causes the inflow to rise toward the water surface. Negative buoyancy occurs under the opposite conditions and causes the opposite effect. The critical temperature difference (ΔT in $^{\circ}$C) which can lead to stratification can be estimated based on the following equation:

$$|\Delta T| = CQ^2/(d^3H^2) \qquad (2)$$

where C = coefficient dependent on inlet configuration, buoyancy type, and tank diameter; Q = inflow rate (cfs or Lpm), H = depth of water (feet or meters), and d = inlet diameter (feet or meters). Based on this relationship, deep reservoirs or ones with large diameter inlets have a greater tendency toward stratification. If significant temperature differences are experienced, then increasing the inflow rate is an effective strategy for reducing the propensity for stratification. Continuous temperature monitoring can be used to assess stratification in reservoirs.

Mixing duration

The duration of mixing in a reservoir should ideally be less than the time it typically takes to fill the reservoir. For a wide range of tank and reservoir designs, experimentation has shown that the mixing time is primarily dependent upon the volume of water in the facility, diameter of the inlet, and the rate of flow (Grayman 2000). Equation (3) was developed for cylindrical reservoirs under fill and draw operation whereby V is volume of water in the reservoir at start of fill, Q is inflow rate, and d is inlet diameter:

$$\text{Mixing time} = 9V^{2/3}(d/Q) \tag{3}$$

Because of the highly significant effect of inlet diameter and amount of water exchanged during the fill cycle on mixing time, it is recommended that inlet diameters be sized in order to ensure adequate mixing.

Managing detention time

Long detention times can lead to low disinfectant residuals, even in well-mixed reservoirs. Detention time can be estimated by dividing the duration of an average fill and draw cycle by the fraction of the water that is exchanged during the cycle (Equation (4)):

$$\text{Average detention time} = [0.5 + (V/\Delta V/)](\tau_f + \tau_d) \tag{4}$$

whereby τ_f is the fill time, τ_d is the draw time, V is the volume of water at start of the fill period, and ΔV is the change in water volume during the fill period (Grayman 2000). The detention time can then be used with the disinfectant decay rate to estimate disinfectant residual.

Flushing the distribution system

To minimize sediment buildup, regular flushing of the pipelines is recommended as part of routine operation of a reclaimed water network. Flushing of distribution systems has three common objectives:

- replacing stale water;
- removing loose deposits; and
- scouring and cleaning the pipe surface to get rid of biofilms.

Flushing should begin from the mains, then proceed to sub-mains, manifolds, and finally to the laterals. Utilities often determine the velocity, duration, and frequency of flushing pipelines with guesswork and generalizations but ‘site-specific’ velocity recommendations may be developed since several processes appear to impact the stability/removability of deposits in distribution mains. Friedman *et al.* (2003) published a site-specific flushing decision tree. At the root of the tree is establishing objectives for flushing and establishing an applicable flushing velocity. The former can aim at removing loose debris or scouring the pipe wall. The degree of pipe tuberculation and particle density are the two most critical factors for predicting the behavior of loose deposits during flushing. Of less importance is particle size and pipe diameter. Flushing velocities of 2.5–3 feet/s (0.76–0.91 m/s) are effective for removing sand and silt debris (Kirmeyer *et al.* in press). At the bare minimum, flushing should be continued until clean water runs from the flushed line for at least 2 min (Haman 2011). Unfortunately, some regulators do not permit flushing of reclaimed water distribution systems (Jjemba *et al.* 2010a). This restriction might compromise the maintenance of the reclaimed water systems as it prevents the removal of accumulated algae, debris, and biofilms. Such restrictions could be circumvented by flushing the water back into the sewer or directly onto greenbelts intended for irrigation with reclaimed water.

COST AND PRICING OF RECLAIMED WATER

Because it is essential for life, water is a priceless resource. However, a lot of investment goes into its purification, treatment, and delivery. These are the services on which water pricing is, at least in theory, based. A focus of the reclaimed water industry’s cost and pricing issues are summarized in Table 13.

The water portfolio

The economic value of reclaimed water to the user depends on: (i) the availability and price of freshwater supplies; and (ii) the reclaimed water supply characteristics. According to the Institute of Public Utilities, the amount individuals pay for potable water in the USA is rising faster than the rate of inflation. It is also faster than the amount paid for any other utility service including gas, electricity, cable, or telephone charges (Beecher 2011). Reclaimed water may be more attractive than potable water for some uses based on

Table 13 | Generic cost and pricing issues and problems identified

• Current rates unable to cover costs	• Perceived low product value
• High capital requirements to meet 'green initiatives'	• Reduction in revenues
• Competing revenue with potable water	• Keeping the cost of reclaimed water below cost of potable water
• Cost of operation versus returns	• Capital cost to increase distribution, use and storage
• Managing treatment costs	

other characteristics such as nutrients and a variety of environmental benefits associated with reusing water (USEPA 1998; Axelrad & Feinerman 2009; Chen & Wang 2009).

Pricing reclaimed water

Setting reclaimed water rates is important in successfully establishing and operating a reclaimed water system. Oftentimes it costs more to generate reclaimed water than it costs to generate potable water (Cuthbert & Hajnosz 1999). If the recycled water has to be treated to a usable level just for disposal, then this cost is borne by the users of the sewage system. To that effect, reclaimed water users are only on the hook for distribution system costs and any treatment above that needed for discharge. Furthermore, reclaimed water costs only have to compete with the most expensive source of potable water. To remain attractive and competitive, reclaimed water cannot be priced higher than potable water as, in the eyes of most consumers, it is generated to supplement potable water supplies. Customers also perceive reclaimed water to be of lower quality than potable water.

Table 14 | Common reclaimed water rate types

Type of rate	Description
Flat rate	A fixed amount of money is paid by the customer over a fixed duration (e.g., \$7/month) irrespective of the amount of water used. It therefore provides for an unlimited use
Commodity-based rate	A fixed amount of money is paid per unit volume of water. For example, \$0.44 per 1,000 L. It is generally for commercial and industrial users
Base plus volume charge	A fixed base charge plus an amount of money charged per unit volume consumed. Example: \$3.25 plus \$0.02 per 1,000 L
Seasonal rate	A lower rate is charged per unit volume used up to a certain volume. Thereafter, a slightly higher rate is charged for medium volumes consumed. An even higher rate is charge for larger volumes used. Example: \$0.27 per first 1,000 L (low volume rate); \$0.32 per next 1,000 L used (medium) and \$0.41 per L thereafter. It is generally for commercial and industrial users
Declining block rate	The rates decline as more volume of water is used. Example: \$0.13 (first block); \$0.03 (second block); \$0.02 (third block). Typically used for agricultural purposes
Inverted block rate	The rates are increased as more volume of water is used. Example: \$0.16 (Tier 1); \$0.20 (Tier 2); \$0.41 (Tier 3); 0.82 (Tier 4), and \$1.64 (Tier 5). It is most suited for non-agricultural purposes
Time-of-day-based rate	Different rates under varying demand scenarios. For example: \$0.34 during peak demand and \$0.31 during off-peak hours. Peaking customer had total average daily demand occurring between 9:00PM and 6:00AM whereas off-peak customers had occurring at a continuous 24 h period
Take-or-pay-based contracts	Customer negotiated rates and terms under service agreements. Can be a single rate or a multi-layered complex rate structure depending on water demand and supply, quality or a variety of other factors
Customer-specific negotiated rate	Rates varying or remaining fixed based on negotiated agreements
Connection fees	A one-time fee for each user before they are connected to the system
Assessment fee	To defray capital cost of the reuse system
Impact fees	Covers cost of wastewater treatment and disposal (i.e., sewer rates)

Sources: Cuthbert & Hajnosz (1999); USEPA (2012a).

However, potable water quality is not needed for most non-potable reclaimed water applications.

A survey of 23 plants by Cuthbert & Hajnosz (1999) found rates of 50–100% those of potable water, with an average price of 75% the price of potable water. Actual pricing was based on:

- a comparable competitive option (i.e., the potable water price);
- maintaining a viable alternative economic alternative;
- incentives for using reclaimed rather than potable water; and/or
- rates that other utilities charge.

However, setting reclaimed water prices below production costs creates a shortfall which has to be made up typically through subsidies. The subsidies are indirect (e.g., sewer fees) or directly from the respective municipality budget. Cuthbert & Hajnosz (1999) and more recently the USEPA (2012a) identified several types of rates for pricing reclaimed water (Table 14). These have more recently been characterized as volumetric fees (USEPA 2012a). Flat rate was the most predominant practice followed by the seasonal rate structure (Cuthbert & Hajnosz 1999). However, by the time of that study connection fees, assessment fees, and impact fees were not a common practice. These three practices were only recently highlighted by the USEPA (2012a).

Many utilities set reclaimed water rates based on market analysis or what customers are willing to pay rather than on full cost pricing. The average reclaimed water rates in 2007 ranged between 50 and 100% of the potable water rate and 42% of respondents set their reclaimed water rates to promote the use of reclaimed water (HDR 2008). Of 89 utilities studied, most recovered less than 25% of their operating costs. However, the pricing did not include significant necessary expenses incurred or savings realized by utilities including the cost of purchasing water rights to new supplies (applicable in the western USA) replaced by the reclaimed water. Also not reflected was the reduction in National Pollutant Discharge Elimination System (NPDES) permitting, permit fees, outfall dilution and mixing requirements, environmental mitigation, human health protection, and more difficult outfall construction avoided by reusing all or a portion of what would have been discharged (Chen & Wang 2009). These beneficial factors are typically non-monetary but Chen & Wang (2009) monetized them and found them economically advantageous. Similar approaches and conclusions have been reported by Liang & van Dijk (2008) and Molinos-Senante et al. (2011).

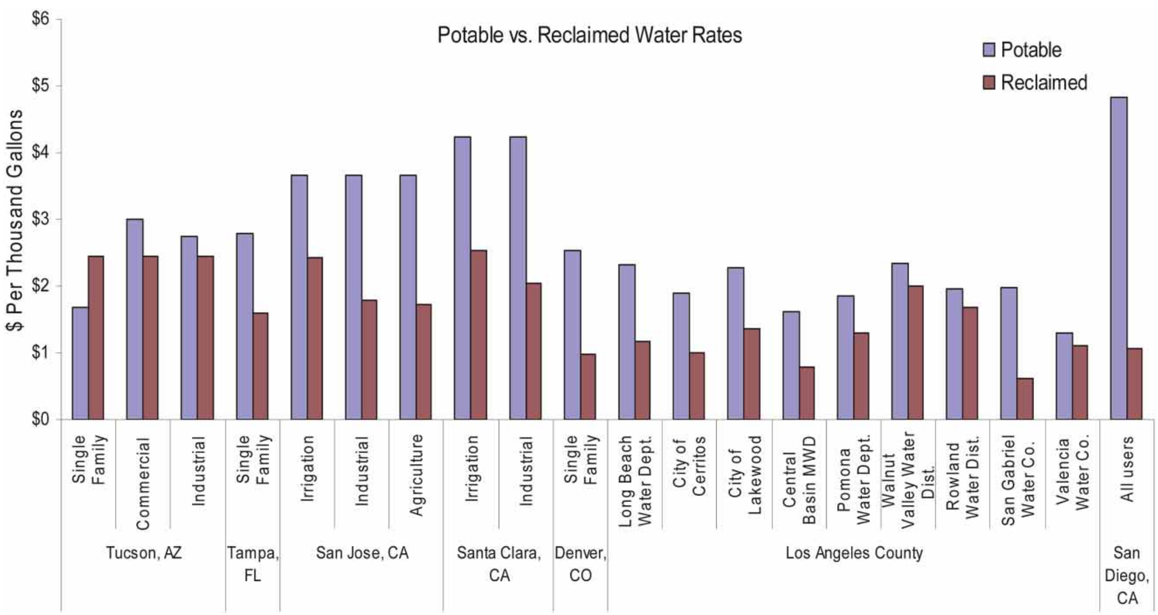

Figure 10 | Potable versus reclaimed water rates (compiled from: http://www.cms3.tucsonaz.gov/water/reclaimed; http://www.sanjoseca.gov/sbwr/rates.htm; http://www.tampagov.net/dept_water/information_resources/rates_and_fees/index.asp; http://www.denverwater.org/BillingRates/RatesCharges/2012Rates/NonPotable/; http://www.lacsd.org; and http://www.sandiego.gov/water/recycled/faq.shtml#else).

Results of an extensive search for potable and reclaimed water rates for some cities in the USA are presented in Figure 10. Reclaimed water was less expensive in all cities for all user types except for the single-family rate in Tucson (AZ). The discrepancy in Tucson may be explained by the cost of the new construction necessary to deliver to single family homes. The largest difference in price was found in San Diego, CA where reclaimed water cost about 78% less than potable for all user types. There is increasing recognition of the need for generating sufficient revenues from reclaimed water systems to provide annual capital improvements, operating and maintenance, repairs, working capital, and reserves (USEPA 2012a). This requires equitably distributing the cost of water services based on cost-of-service principles. This strategy strengthens the water portfolio.

CONCLUSION

Water reclamation has continued to grow in urban and rural areas of the USA. Most of the focus has until now been with meeting effluent standards. However, reclaimed water is a perishable product. Exploiting its full benefit requires maintaining acceptable shelf life and proper preservation at the point of use. Attaining this goal is still hampered by infrastructural, customer-relations, quality, operational, costing, demand and supply shortfall, regulations as well as workforce problems. The first five problem areas on the list represented 80% of the issues raised through the survey. Solutions to most of these problems can be explored from information already available in the gray and peer-reviewed literature together with a concerted effort to tap the indigenous knowledge from operators and water professionals. Such an approach will be crucial in formulating best management practices for reuse. The information presented in this review will play a significant role in meeting this goal.

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