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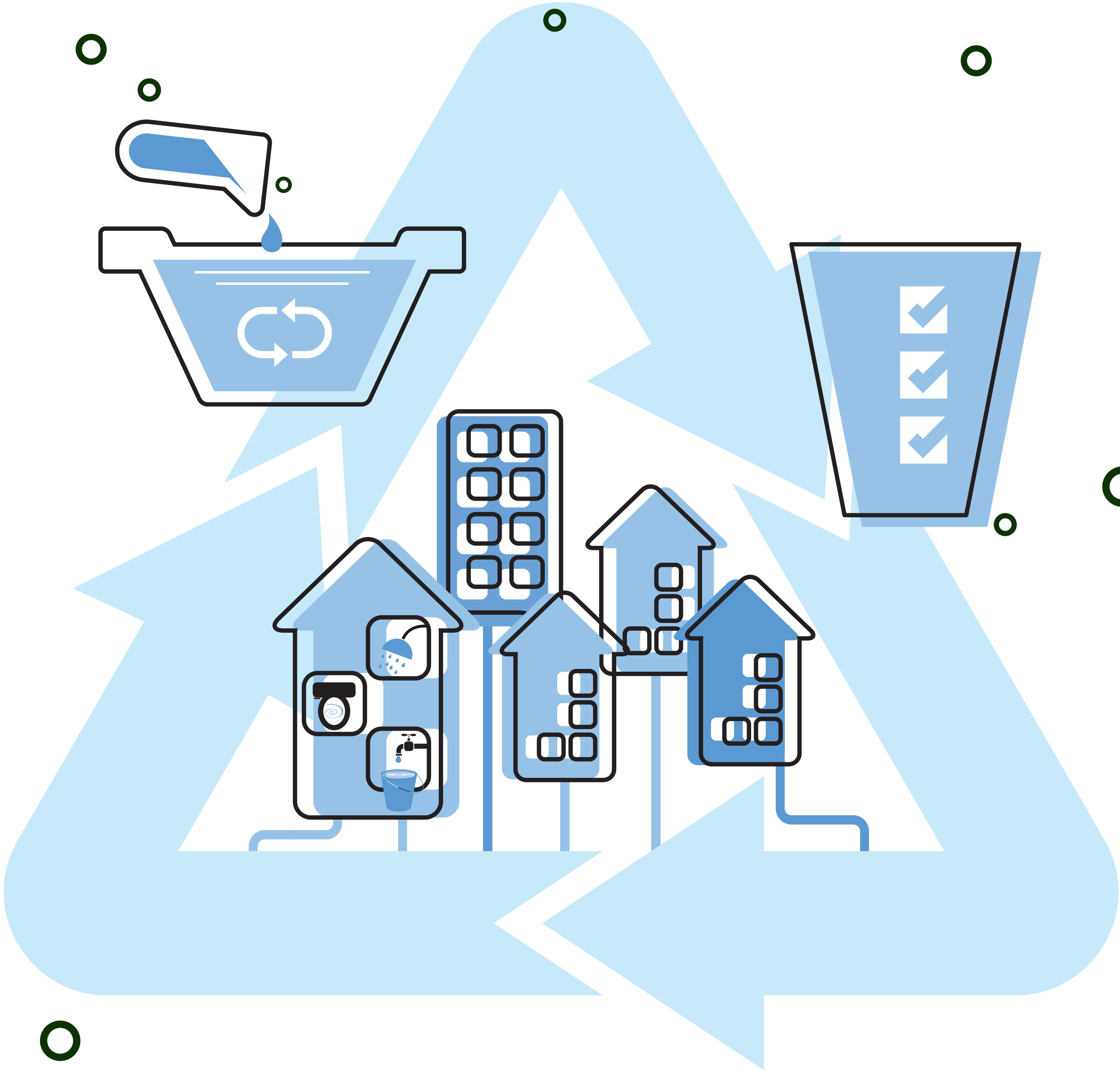

POTABLE REUSE

GUIDANCE FOR PRODUCING SAFE DRINKING-WATER

World Health Organization

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Potable reuse: Guidance for producing safe drinking-water

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ABBREVIATIONS AND ACRONYMS

AMD	acid mine drainage
AOP	advanced oxidation process
ARB	antibiotic resistant bacteria
ARG	antibiotic resistance genes
ASP	activated sludge process
AWRP	advanced water recycling plant
BAC	biological activated carbon
BMD	benchmark dose
BMDL	lower confidence limit on the benchmark dose
BNR	biological nutrient reduction/removal
CCP	critical control point
CECs	chemicals/contaminants of emerging concern
CFU	colony-forming unit
CRMWD	Colorado River Municipal Water District (USA)
CSF	cancer slope factor
Ct	product of disinfectant concentration and contact time
DALYs	disability-adjusted life years
DBPs	disinfection by-products
DOC	dissolved organic carbon
DPR	direct potable reuse
ESB	engineered storage buffer
GAC	granular activated carbon
GDWQ	Guidelines for Drinking-water Quality (WHO)
GL	gigalitre
GWR	groundwater replenishment
H_2O_2	hydrogen peroxide
IPR	indirect potable reuse
LMWD	Laguna Madre Water District (USA)
LOAEL	lowest-observed-adverse-effect level
LRV	log_{10} reduction value
MBR	membrane bioreactor
MF	microfiltration
MGD	million gallons per day
MLD	million litres per day
NDMA	*N*-nitrosodimethylamine
NF	nanofiltration
NIWR	National Institute for Water Research (South Africa)
NOAEL	no-observed-adverse-effect level
NTU	nephelometric turbidity unit
NWRI	National Water Research Institute (USA)
OCSD	Orange County Sanitation District (USA)
OCWD	Orange County Water District (USA)
OWMP	Occoquan Watershed Monitoring Program (USA)

ozone-BAC	ozone-biological activated carbon
PCBs	polychlorinated biphenyls
PCR	polymerase chain reaction
PDU	PCR detectable units
pppy	per person per year
PUB	Public Utilities Board - National Water Agency (Singapore)
RO	reverse osmosis
SAT	soil-aquifer treatment
SCADA	supervisory control and data acquisition
SSP	sanitation safety plan
TDI	tolerable daily intake
TDS	total dissolved solids
TOC	total organic carbon
UF	ultrafiltration
UOSA	Upper Occoquan Service Authority (USA)
USA	United States of America
USEPA	United States Environmental Protection Agency
UV	ultraviolet
VOC	volatile organic compound
WHO	World Health Organization
WRP	water reclamation plant
WRRF	WateReuse Research Foundation
WSP	water safety plan
WWTP	wastewater treatment plant

1. INTRODUCTION

KEY MESSAGES

1. **Potable reuse represents a realistic, practical and relatively climate independent source of drinking-water.**
2. **Potable reuse schemes will be complex and proponents will need to have sufficient resources and capabilities for successful implementation.**
3. **Management of potable reuse schemes should be based on the framework for safe drinking-water, including water safety plans (WSPs).**
4. **The first step in developing WSPs is to assemble a dedicated team with appropriate expertise in all aspects of potable reuse from wastewater collection to treatment and delivery of drinking-water to consumers.**

1.1 Purpose of this guidance

Potable reuse can represent a realistic and practical source of drinking-water in many circumstances. The purpose of this guidance is to describe how to apply appropriate management systems to the production of safe drinking-water from municipal wastewater. At meetings of drinking-water quality experts convened by WHO in 2013 and 2014, it was agreed that further guidance is required to assist drinking-water providers and regulators on how to plan, design and operate potable reuse schemes. The need for guidance is based on increasing interest and development of potable reuse schemes in response to growing pressures on available water resources. The scope of the guidance includes both direct and indirect potable reuse (DPR and IPR) and, unless otherwise specified, the term potable reuse refers to both DPR and IPR (see Box 1.1).

The principles described in the WHO Guidelines for Drinking-water Quality (GDWQ) (WHO, 2017a) apply to potable reuse, but implementation involves consideration of particular issues associated with source water quality and complexity of potable reuse schemes. The purpose of this document is to build upon the guidance provided in the GDWQ and a previous report on potable reuse (WHO, 1975) with information on specific aspects of potable reuse, including the quality and protection of source waters, types of treatment processes, additional monitoring considerations, potential use of environmental buffers and engineered storages, and public acceptance. The guidance follows a similar approach to the GDWQ in providing information on water quality and effective management and performance of potable reuse schemes. It does not provide detailed technical design criteria for technologies used in potable reuse. No new guideline values or principles are introduced.

The guidance is intended for use by drinking-water suppliers and regulators who are familiar with the GDWQ and, in particular, the “framework for safe drinking-water” including WSPs. As the starting point of potable reuse schemes is untreated wastewater, proponents should also be aware of the potential application of sanitation safety plans (SSPs) (WHO, 2015a). The guidance could also be useful to others with an interest in potable reuse, including environmental health and water resource professionals.

1.2 Drivers for potable reuse

Population growth, increased urbanization, catchment pressures, expanding areas of water scarcity and the impacts of climate change on water availability are all increasing pressures on existing drinking-water resources, resulting in the need to identify new or alternative sources of drinking-water supply. Between 2014 and 2050 the world population is expected to increase by 33% from 7.2 billion to 9.6 billion (UNDESA, 2014). During this period, urban populations are projected to grow by 61% from 3.9 billion to 6.3 billion, with the largest increases expected in Asia and Africa. This projection means that the percentage of people living in urban areas will increase from 54% to 66%, with urbanization in 89 countries expected to exceed 80% (UNDESA, 2014). At the same time droughts and flooding associated with climate change and climate variability are also increasing pressure on water supplies (World Water Assessment Programme, 2009; IPCC, 2014; UNESCO, 2017).

One response is to reduce vulnerability to these impacts by increasing resilience, diversity, adaptability and sustainability of drinking-water supplies. Developing new and preferably more climate independent water resources in close proximity to major population centres should be a priority. Potable reuse and, in coastal areas, seawater desalination meet this definition.

Box 1.1 Definitions for potable reuse

Wastewater is liquid waste discharged from homes and other residential premises, commercial and industrial premises and similar sources, to individual disposal systems or to municipal sewer pipes. It contains mainly human excreta and used water. Wastewater collected in municipal sewerage systems is called municipal wastewater or municipal sewage. In well-operated sewerage systems, contributions of industrial contaminants are reduced by management of industrial waste discharges (e.g. through pre-treatment).

Indirect potable reuse (IPR) represents the planned addition of treated wastewater into water bodies used as sources of drinking-water. The water bodies, which can include rivers, lakes, reservoirs and aquifers, are referred to as environmental buffers. Water containing a proportion of treated wastewater is taken from the environmental buffer and further treated to provide drinking-water.

Direct potable reuse (DPR) represents the introduction of treated wastewater (with or without retention in an engineered storage) into a drinking-water supply without prior discharge to an environmental buffer. The treated wastewater may be blended with raw water from a river, lake, reservoir or aquifer immediately before a drinking-water treatment plant; blended with treated water downstream of a conventional drinking-water treatment plant; or introduced directly into a drinking-water distribution system.

Unplanned potable reuse (also known as unacknowledged or de facto potable reuse) represents various descriptions of the long-standing and common practice of producing drinking-water from water sources impacted by wastewater discharges. This is particularly common in river systems serving multiple urban centres where discharged wastewater (treated or untreated) becomes part of the water resource used by downstream centres. Providing that appropriate control measures, including treatment are applied, drinking-water supplies incorporating unplanned potable reuse are capable of producing safe drinking-water.

Potable reuse can produce large volumes of drinking-water from wastewater available from established collection systems in both coastal and inland locations. In addition, it can reduce negative impacts of microbial hazards and in some cases nutrients from wastewater discharges on marine and freshwater environments (Table 1.1) (UNESCO, 2017). Urban settlements represent the main point sources of coastal and riverine water pollution with wastewater discharges being significant contributors (World Water Assessment Programme, 2009; UNESCO, 2017).

The number of potable reuse schemes is increasing. From the pioneering starts in the 1960s of IPR at Montebello Forebay (USEPA, 2012a) and DPR at Windhoek in 1969 (Du Pisani, 2006), potable reuse systems have been established in several continents, including Africa, Asia, Australia, Europe and North America (Table 1.2). A number of these schemes are discussed in case studies included in this document (see Appendix 5). The majority of potable reuse schemes have been developed in the 21st century and it is expected that potable reuse will increase as populations and pressure on finite water resources continue to grow.

Economically and practically, potable reuse compares favourably with seawater desalination, which is also increasing in use. In some cases, such as Singapore and Perth (Australia), desalination is used in combination with potable reuse. Limitations of seawater desalination are that it is restricted to coastal areas and has high energy use. Except for schemes involving pumping to distant environmental buffers (where used), potable reuse is less expensive than seawater desalination (Freeman et al, 2008; Law, 2008; NRC, 2012; ATSE, 2013; Tchobanoglous et al, 2015).

Table 1.1 Advantages and challenges of potable reuse

Advantages	Challenges
• Climate independent water supply • Existing collection systems and, in many cases, established conventional treatment processes in close proximity to population centres • Reduced environmental impacts from discharges (particularly from microbial hazards and in some cases from nutrients) • Typically less expensive than seawater desalination • Growing public acceptance	• Source wastewaters are very poor quality with high concentrations of microbial pathogens and can potentially contain a broad range of chemical contaminants • Generally includes use of complex treatment processes and a high level of technical expertise and understanding • Consequences of failure could be high • While public acceptance is growing, concerns about the use of wastewater as a source of drinking-water need to be addressed by education and public participation

1.3 Challenges of potable reuse

Potable reuse involves producing safe drinking-water from wastewater. Due to the very poor microbial quality of municipal wastewaters and threats from chemical contamination, potable reuse is often a complex activity generally involving advanced treatment processes and substantial management expertise (Table 1.1). It can involve coordination of separate wastewater and drinking-water treatment plants. Before proceeding, proponents should ensure that they have sufficient resources and capabilities (financial, technical and operational) to implement potable reuse schemes safely and sustainably. The consequences of poor design or failure of control measures are substantial.

1.4 Direct and indirect potable reuse

Both DPR and IPR generally involve advanced treatment of wastewater to produce drinking-water. The point of difference between DPR and IPR is the use of environmental buffers in IPR (see Box 1.1). The claimed benefits of environmental buffers vary and include provision of a diluting step, blending, additional contaminant attenuation[1] processes, time to respond to treatment failure and reduction of negative public perceptions (ATSE, 2013).

From the commencement of planned potable reuse in the 1960s, most of the focus and the development of schemes has involved IPR (Table 1.2). Indirect potable reuse schemes have been developed using a variety of surface water and groundwater environmental buffers and treatment configurations. They are well established, accepted and have a long history of successful operation (NRC, 1998; 2012). However, in recent years there has been increased support for DPR including from the American National Research Council and other sources (Leverenz et al, 2011; NRC, 2012; ATSE, 2013; Tchobanoglous et al, 2015; TWDB, 2015; NWRI, 2016; Olivieri et al, 2016). The numbers of DPR schemes are increasing with development of small schemes in Beaufort West (South Africa), Cloudcroft (New Mexico, United States of America [USA]) and Big Spring (Texas, USA) (Burgess, 2015; Dahl, 2014; Drewes & Horstmeyer, 2015).

Similar to IPR, DPR can involve a number of configurations with treated wastewater and conventional water sources mixed before or after treatment (ATSE, 2013; Tchobanoglous et al, 2015; Drewes & Horstmeyer, 2015; Olivieri et al, 2016). Advantages of DPR include that it avoids potential contamination of treated wastewater in environmental buffers, particularly those involving surface water. Direct potable reuse avoids issues over water access rights, reducing pumping and transport costs and can be applied in locations where suitable environmental buffers are not available (Leverenz et al, 2011; ATSE, 2013). However, a perceived disadvantage of DPR compared with IPR is that the lack of an environmental barrier reduces the time available to respond to treatment failures and other incidents that could impair drinking-water quality prior to supply to consumers. In this respect DPR is similar in nature to traditional drinking-water treatment plants. To some extent the lack of an environmental buffer can be compensated through the use of constructed storages to monitor water quality after treatment and before supply. While detention times will typically be much shorter than those in environmental buffers, engineered storage buffers (ESBs) can provide an increased capacity to assess and interrogate operational monitoring results and to implement responses before supply of water to consumers (Tchobanoglous et al, 2011; Leverenz et al, 2011; ATSE, 2013; Cotruvo, 2014). Responses could involve actions ranging from substituting alternative sources of water to issuing public notifications. Engineered storages can also be important in the more traditional role of providing buffering storages to deal with variations in water demand.

[1] Attenuation can include biotransformation and photolysis of organic chemicals (Fono et al, 2006) and inactivation, removal and reduced infectivity of microbial pathogens by natural ultraviolet (UV) light and predation.

Table 1.2 Examples of established potable reuse schemes

Scheme	Type	Environmental buffer (IPR only)	Start date	Treatment process (after secondary wastewater treatment)
Montebello Forebay, Los Angeles County, California, USA	IPR	Groundwater	1962	Media filtration, SAT, Cl_2
Old Goreangab plant, Windhoek, Namibia	DPR	—	1969–2002 (replaced)	Algae flotation, chemical clarification, media filtration, GAC, Cl_2
New Goreangab plant, Windhoek, Namibia	DPR	—	2002	O_3, DAF, rapid sand filtration, O_3, BAC, GAC, UF, Cl_2
Water Factory 21, Orange County, California, USA (replaced, see below)	IPR	Groundwater	1976–2004 (replaced)	Lime clarification, media filtration, GAC, Cl_2 RO added 1977, AOP (UV/H_2O_2) added 2001
Groundwater Replenishment System, Orange County, California, USA	IPR	Groundwater	2008	Cl_2, MF, RO, AOP (UV/H_2O_2)
Upper Occoquan Service Authority, Fairfax County, Virginia, USA	IPR	Surface water	1978	Lime clarification, media filtration, GAC, Cl_2, chloramination
Hueco Bolson recharge project, El Paso Water Utilities, Texas, USA	IPR	Groundwater	1985	PAC, lime clarification, media filtration, O_3, GAC, O_3, Cl_2
Clayton County Water Authority, Georgia, USA	IPR	Surface water	1985	Land application, UV, Cl_2
West Basin water recycling plant, California, USA	IPR	Groundwater	1995	MF, RO, AOP (UV/H_2O_2), NH_2Cl
Langford Recycling Scheme, Chelmsford, UK	IPR	Surface water	1997	UV
Gwinnett County, Georgia, USA	IPR	Surface water	1999	Chemical phosphorus removal, UF, O_3, GAC
Scottsdale Water Campus, Arizona, USA	IPR	Groundwater	1999	Media filtration, MF, RO, Cl_2
Torreele, Wulpen, Belgium	IPR	Groundwater	2002	UF, RO, UV
NEWater, Singapore	IPR	Surface water	2003	UF, RO, UV
Los Alimitos, Water Replenishment District of Southern California, USA	IPR	Groundwater	2005	MF, RO, UV
Chino Basin groundwater recharge project, Inland Empire Utility Agency, California, USA	IPR	Groundwater	2007	Media filtration, SAT, Cl_2
Arapahoe County/Cottonwood, Colorado, USA	IPR	Groundwater	2009	Media filtration, RO, AOP (UV/H_2O_2), Cl_2
George, South Africa	IPR	Surface water	2009/2010	UF, Cl_2
Prairie Waters Project, Aurora, Colorado, USA	IPR	Groundwater	2010	Riverbank filtration, AOP (UV/H_2O_2), BAC, GAC, Cl_2
Beaufort West, South Africa	DPR	—	2010	Media filtration, UF, RO, AOP (UV/H_2O_2), Cl_2
Permian Basin, Colorado River Municipal Water District, Texas, USA	IPR	Surface water	2012	UF, RO, AOP, Cl_2
Dominguez Gap Barrier, Los Angeles, California, USA	IPR	Groundwater	2012	MF, RO
Big Spring, Texas, USA	DPR	—	2013	MF, RO, AOP (UV/H_2O_2), blending, media filtration, Cl_2
Beenyup groundwater replenishment scheme, Perth, Australia	IPR	Groundwater	2016	UF, RO, UV
Cloudcroft, New Mexico, USA	DPR	—	Being developed	MBR (enhanced secondary treatment), Cl_2, RO, AOP (UV/H_2O_2), blending, UF, UV, GAC, Cl_2

Notes: AOP = advanced oxidation process, BAC = biological activated carbon, BNR = biological nutrient removal, Cl_2 = chlorination, DAF = dissolved air flotation, GAC = granular activated carbon, H_2O_2 = hydrogen peroxide, MBR = membrane bioreactor, MF = microfiltration, NH_2Cl = monochloramine, O_3 = ozonation, PAC = powdered activated carbon, RO = reverse osmosis, SAT = soil-aquifer treatment, UF = ultrafiltration, UV = ultraviolet light.
Source: Adapted from Drewes & Khan (2011), USEPA (2012), Gerrity et al (2013b), Burgess (2015), Onyango et al (2015).

1.5 Unplanned potable reuse

There has been increased discussion about similarities between planned IPR and long-standing practices of using drinking-water sources impacted by wastewater discharges (Asano et al, 2007; NRC, 2012). The latter is variously referred to as unplanned, unacknowledged or de facto potable reuse. The term unplanned potable reuse is used in this document. Although the presence of such discharges in drinking-water catchments represents a potential source of hazards to drinking-water supplies and is not ideal, it is a common reality (Asano et al, 2007; Rice & Westerhoff, 2015; WHO, 2017a). In these circumstances, wastewater treatment and use of drinking-water treatment commensurate with source water quality are essential. Providing appropriate control measures are applied, drinking-water supplies incorporating unplanned potable reuse are capable of delivering safe drinking-water (Asano et al, 2007; WHO, 2017a).

While the addition of various amounts of wastewater to drinking-water supplies through unplanned potable reuse is common, there are important advantages associated with planned potable reuse. The act of planning can improve quality assurance by providing increased control on the quantities of treated wastewater of typically higher quality added to drinking-water sources and better management of impacts on water quality. Planned potable reuse typically includes extensive monitoring of receiving waters, while this is less common or less frequent in unplanned potable reuse. Although the volume contribution of unplanned reuse is often low, there are examples where wastewater represents a substantial proportion of river flows, particularly during low flows (Swayne et al, 1980; NRC, 2012; Rice & Westerhoff, 2015). However, the impacts of these flows on water quality at intakes to drinking-water supplies have often not been quantified, particularly in relation to microbial quality. The impacts of transport and natural attenuation processes (e.g. distance, dilution, loss of infectivity, predation and inactivation) on microbial contaminants have received limited attention. These knowledge gaps limit the value of comparisons between planned and unplanned potable reuse.

Irrespective of this discussion, the important point is that whatever the source water, the end product should meet drinking-water quality requirements. This can best be achieved through developing and implementing risk-based WSPs incorporating control measures based on the multiple-barrier approach, to collectively deal with identified risks to ensure that health-based requirements are met. This principle applies equally to planned and unplanned potable reuse. The influence of wastewater discharges in unplanned potable reuse is often under-estimated and has been associated with documented outbreaks associated with contaminated drinking-water (Hrudey & Hrudey, 2004; 2014). If properly managed, both planned and unplanned potable reuse can produce safe drinking-water.

1.6 Implementation of potable reuse

Ensuring the consistent supply of safe drinking-water from all drinking-water schemes, including from potable reuse, requires the application of the framework for safe drinking-water, as described in the GDWQ. The framework includes three components:

- **Health-based targets:** These are risk-based measurable objectives that define the safety of drinking-water. They include performance targets to achieve microbial safety and numerical water quality targets for chemical and radiological parameters.
- **Water safety plans:** A comprehensive risk assessment and risk management approach developed and implemented by water suppliers. A WSP includes:
  - **System assessment** to identify, assess and ensure management of public health risks along the water supply chain. Key activities include describing the water supply system; identifying hazards and hazardous events and assessing the associated risks; determining and validating control measures, reassessing and prioritizing the risks; and developing, implementing and maintaining an improvement/upgrade plan.
  - **Monitoring** to determine whether the control measures put in place are effective, that the WSP is being implemented in practice and that the system, as a whole, is effective and achieving health-based targets. Key activities include defining monitoring of the control measures and verifying the effectiveness of the WSP.
  - **Management and communication** to ensure that appropriate operational and management systems are in place to support and sustain water safety. Key activities include preparing management procedures (including incident protocols) and developing supporting programmes.
- **Independent surveillance:** Activities undertaken by the regulatory agency to ensure that WSPs are being implemented effectively and that health-based targets are being met.

WSPs for potable reuse need to apply to all steps of supply, from collection of wastewater through treatment, distribution and supply to consumers. In some cases, wastewater management might be described in a separate SSP (WHO, 2015a), particularly when different entities are responsible for wastewater management and provision of drinking-water. Sanitation safety plans are based on the same principles as WSPs. As in WSPs, SSPs apply a preventive risk management approach to the entire sanitary system from wastewater generation to end use. The core components of SSPs are system assessment, monitoring, and management and communication.

Where both forms of safety plans are used, they will need to be coordinated to ensure that the overall scheme functions effectively. For example, the outcomes from a SSP on identifying hazardous events; assessing or validating existing control measures; assessing exposure risks; monitoring control measures; and verification of performance should feed into the WSP. The WSP, which will have primacy in ensuring the safety of potable reuse, should include or reference all key elements associated with managing the schemes, from wastewater collection to delivery of drinking-water at customers' taps. This guidance will focus on design and implementation of WSPs.

1.7 Stakeholder engagement

1.7.1 Assembling a water safety plan team

A qualified team with sufficient technical expertise and breadth of knowledge is needed to implement potable reuse schemes. Assembling this team should be the first step in developing a WSP. The team should be assembled by the drinking-water supplier and will include representatives from the supplier as well as a wider group of stakeholders. The number and type of stakeholders involved in potable reuse schemes will be influenced by the nature and complexity of the scheme and existing arrangements for wastewater management and production of drinking-water. For example, IPR with aquifer or reservoir storage may involve more stakeholders than DPR and can include water resource and environment protection agencies (Angelotti & Grizzard, 2012; NRC, 2012). In some cases, wastewater management and drinking-water supply is undertaken by one agency (Seah & Woo, 2012) while in others, responsibilities can be split (Angelotti & Grizzard, 2012). Irrespective of the number of entities involved in potable reuse schemes, it is essential that all activities associated with wastewater management and production of drinking-water are coordinated, and communication between all entities is maintained. Water safety plan teams should consult with and, where appropriate, include representatives of each stakeholder to provide a comprehensive understanding of all components of the water supply system, including the wastewater system, environmental buffers (if used) and the drinking-water system. Representatives from SSP teams should be included where these are used to manage wastewater treatment plants (WWTPs).

1.7.2 Public engagement

A key to successful implementation of potable reuse is planned and targeted public engagement to build acceptance, confidence and trust. Critical steps in the process are agreement that drinking-water supplies require augmentation with new water sources and, that after consideration of plausible alternatives, potable reuse is the preferred and accepted choice. There have been examples where potable reuse schemes have not proceeded due to public opposition. There is also evidence that public acceptance can be achieved, with the support of successful engagement programmes leading to schemes proceeding.

1.8 Scope of this guidance

This document applies to planned potable reuse of treated wastewater including both DPR and IPR. Unplanned potable reuse is not included within the scope of this document.

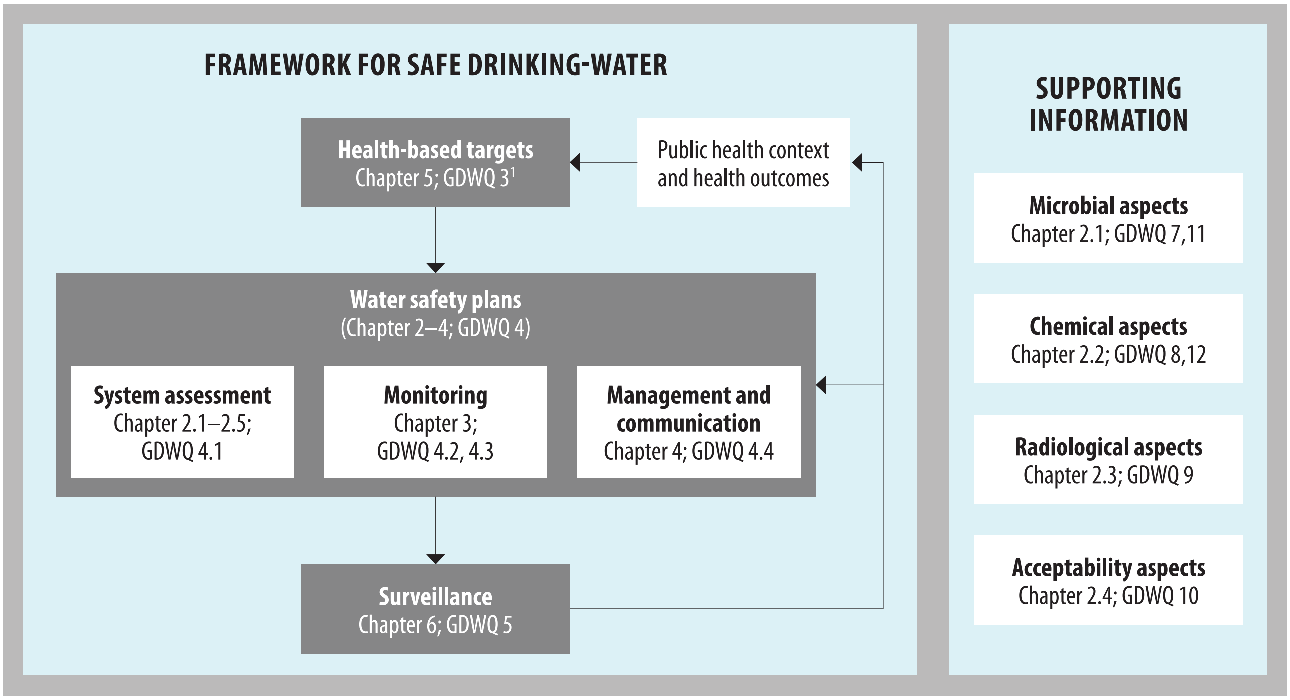
The document is based on the principles of the framework for safe drinking-water, including the key WSP components of system assessment, monitoring, and management and communication (Figure 1.1). The intent is not to repeat general information provided in the GDWQ but rather to focus on specific issues and characteristics that are relevant to potable reuse, including the high concentrations of microbial pathogens and wide array of chemical hazards potentially present in wastewater, wastewater management, specific treatment options such as advanced oxidation and the use of environmental buffers or engineered storages as control measures. General information provided in the GDWQ and supporting resources, such as the Water Safety Plan Manual (Bartram et al, 2009) and associated texts that support WSP development and implementation, can be consulted for additional guidance.[2]

[2] http://www.who.int/water_sanitation_health/water-quality/safety-planning/en/
http://www.who.int/water_sanitation_health/sanitation-waste/en/

Chapters are provided on:

- Chapter 2 **(System assessment: Hazard identification and control measures)** includes information on microbial, chemical and radiological hazards and acceptability parameters as well as information on identification and validation of potential control measures. Corresponding chapters in the GDWQ are 4.1 (system assessment) and 7–10 (microbial, chemical, radiological and acceptability aspects).
- Chapter 3 **(Monitoring)** includes information on operational monitoring and verification. Corresponding chapters in the GDWQ are 4.2 (operational monitoring and maintaining control) and 4.3 (verification).
- Chapter 4 **(Management and communication: Incident protocols)**. The corresponding chapter in the GDWQ is 4.4 (management procedures).
- Chapter 5 **(Health-based targets)** includes information on microbial performance targets, chemical guideline values and radiological screening levels and guidance levels. Corresponding chapters in the GDWQ are 3 (health-based targets), 7.2 (microbial aspects: health-based target setting), 8.2 (derivation of chemical guideline values and health-based values) and 9 (radiological aspects).
- Chapter 6 **(Regulations and independent surveillance)**. The corresponding chapters in the GDWQ are 2.7 (drinking-water regulations and supporting policies and programmes) and 5 (surveillance).
- Chapter 7 **(The art of public engagement)**. The inclusion of a specific chapter on stakeholder engagement reflects the importance of this issue to implementation of potable reuse.

Figure 1.1 The framework for safe drinking-water and supporting information



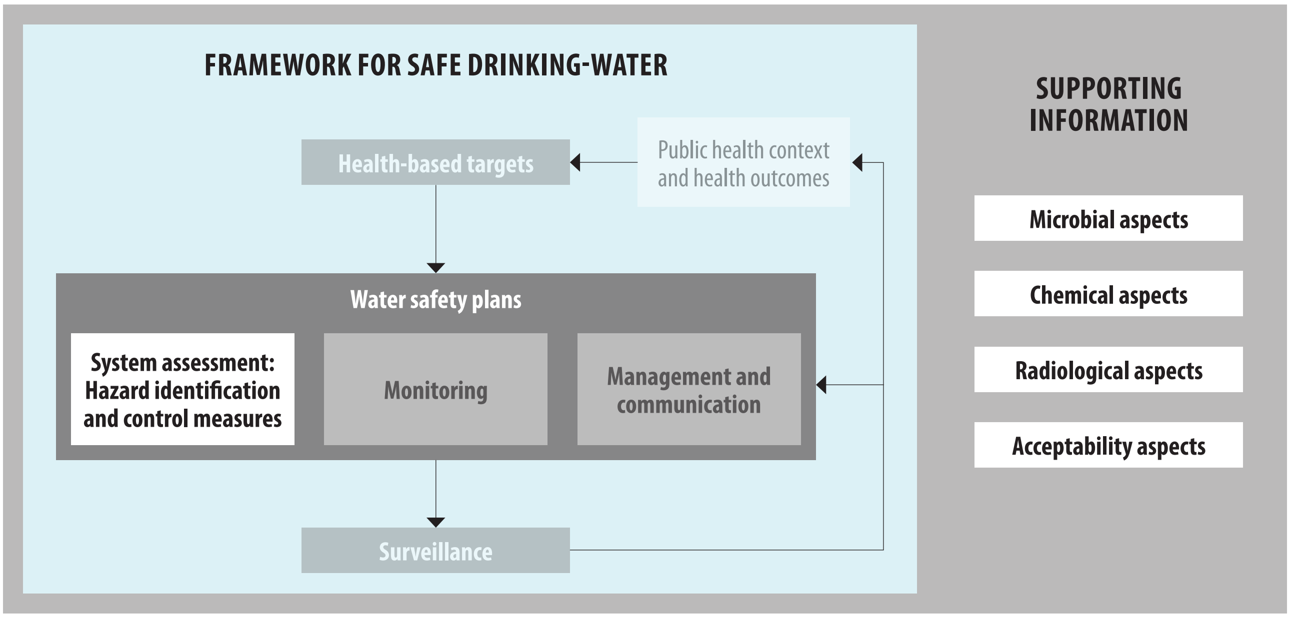
[1] Chapters in this guidance and corresponding chapters in the GDWQ (WHO, 2017a).

A number of case studies are also provided to illustrate successful development of potable reuse schemes. The case studies include discussions of potable reuse in:

- Windhoek, Namibia (DPR)
- Orange Country California, USA (IPR)
- Upper Occoquan Service Authority, Virginia, USA (IPR)
- Singapore (IPR)
- Perth, Australia (IPR)
- Big Spring and Laguna Madre, Texas, USA (DPR)
- eMalahleni, South Africa (DPR using acid mine drainage [AMD] water).

The case studies demonstrate a diversity of approaches and settings and include coastal and inland schemes, IPR with groundwater and surface water buffers, and DPR using wastewater and AMD as source waters. In the case of Singapore and Perth, the potable reuse schemes are part of multiple source systems including traditional water supplies and desalination showing that combinations of sources can increase resilience.

2. SYSTEM ASSESSMENT: HAZARD IDENTIFICATION AND CONTROL MEASURES



KEY MESSAGES

1. Untreated wastewater as a source for potable reuse can contain high concentrations of enteric pathogens. These represent the highest risk to the safety of potable reuse schemes.
2. A broad array of chemical hazards can be present in wastewater, including industrial, commercial and domestic.
3. Concentrations of chemicals/contaminants of emerging concern (CECs) such as pharmaceuticals and personal care products are generally low (ng to µg per L).
4. Control measures should be applied from collection of wastewater to delivery of drinking-water to consumers. Control measures at the source include requirements on industrial discharge quality and changing wastewater collection areas to reduce or eliminate industrial discharges.
5. Potable reuse generally requires complex treatment trains with high levels of reliability. Control measures need to be validated.
6. Environmental buffers used in IPR can provide time to detect and respond to failures, storage capacity, contaminant removal and dilution. However, they can reduce the purity of highly treated wastewater by the addition of natural organic matter, naturally occurring chemicals (from groundwater) and enteric pathogens.
7. Engineered storages can provide time to respond to water concerns, including treatment failures (primarily associated with microbiological quality).
8. Issues to be considered when blending DPR water with other sources of drinking-water include the need to stabilize DPR water to reduce impacts on treatment performance, (including disinfection and formation of disinfection by-products – DBPs) and corrosion. Potential impacts of IPR on environmental buffers also need to be considered.

While WSPs apply equally well to all types of drinking-water supplies, there are specific characteristics of potable reuse schemes that need to be considered as part of system assessment. These include the high concentrations of microbial pathogens in wastewater and potential presence of a wide range of industrial, commercial and domestic chemicals.

The GDWQ and supporting documents (listed in Annex 1 of the GDWQ) provide a comprehensive discussion of microbial, chemical and radiological public health hazards and acceptability parameters that can potentially influence the quality of drinking-water. This information is particularly relevant to wastewater, which by its nature can contain a broad array of contaminants.

Although there are numerous hazards that can compromise drinking-water produced by potable reuse schemes, not all will represent significant risks to human health. Risks need to be assessed and prioritized by determining the likelihood of occurrence at significant concentrations and the probability and severity of consequences if inadequate control measures are applied. Health-based-targets provide the mechanism for defining significant concentrations (see Chapter 5).

To address the higher concentrations of microbial pathogens and wide array of potential chemical contaminants, potable reuse schemes typically incorporate complex combinations of control measures, including industrial discharge management, water and wastewater treatment processes, and the use of natural systems to provide high levels of pathogen removal and protection against chemical hazards. Due to the higher levels of microbial contaminants in wastewater, there is an increased need, during the design of potable reuse schemes, to ensure that the performance of control measures is validated, to demonstrate that they are capable of providing the required levels of hazard reduction.

2.1 Microbial hazards

Unsafe drinking-water can be a significant source of enteric pathogens with the potential to cause large outbreaks, such as the cryptosporidiosis outbreak in Milwaukee (MacKenzie, 1994; Hrudey & Hrudey, 2004; 2014). As described in this guidance and the GDWQ, protecting public health from waterborne illness caused by microbial hazards is of paramount importance.

One of the challenges for potable reuse is that it involves closing the gap between wastewater and drinking-water systems. By design, municipal wastewater systems collect pathogens, particularly those transmitted by the faecal-oral route, with the intent of separating them from communities as well as drinking-water sources. Pathogens that can be found in wastewater are diverse in characteristics and behaviour and include bacteria, viruses, protozoa and helminths (Table 2.1). The greatest risk from exposure to wastewater is gastrointestinal disease following ingestion of enteric pathogens, but other routes of transmission such as inhalation of aerosols or dermal contact can also lead to disease.

Most of the enteric pathogens that cause gastrointestinal illnesses, with the notable exception of *Vibrio cholerae*, do not grow or survive indefinitely in water. Hence, the prevalence and concentration of these pathogens in wastewater will reflect the types and rates of disease in the community. Ranges of reported concentrations in untreated wastewater are provided in Table 2.2. In contrast, so-called free-living pathogens, such as *Legionella* and mycobacteria, which are generally transmitted by routes other than ingestion, can grow under favourable conditions in treated water and associated biofilms, and, in some cases, can survive within amoeba, in distribution systems (Marciano-Cabral et al, 2010).

As a general note, care should be taken in interpreting microbial data as reported pathogen concentrations can be derived using different methods, such as microscopy, culture and detection of genetic material using polymerase chain reaction (PCR) and next generation sequencing. Culture-based methods tend to be time consuming and are not available for all pathogens but have the advantage of detecting living organisms. Tests using PCR and next generation sequencing are much quicker and are powerful tools for detecting the physical presence of microbial pathogens or components of pathogens, but do not generally determine viability or infectivity.

Occasionally, emerging pathogens arise with possible links to water and wastewater. In the past 40 years, this has included pathogens such as *Campylobacter* and *Cryptosporidium* (WHO, 2003). Discharge in faecal material and collection of these pathogens by municipal wastewater systems does not automatically mean that transmission through water and wastewater represents a health risk and this needs to be assessed as emerging pathogens arise. For example, the likelihood of transmission of pathogens such as avian influenza (H5N1), severe acute respiratory syndrome, coronaviruses and Ebola virus through wastewater and drinking-water is extremely low (WHO, 2014; 2017a; CDC, 2014).

Table 2.1 Examples of water/wastewater-borne enteric pathogens

Pathogen	Type species	Illness
Bacteria		
Burkholderia	*B. pseudomallei*	Melioidosis
Campylobacter	*C. coli, C. jejuni*	Gastroenteritis, Guillain–Barré syndrome
Escherichia coli - diarrhoeagenic		Gastroenteritis
Escherichia coli - enterohaemorrhagic	*E. coli* 0157	Gastroenteritis, haemolytic uremic syndrome
Legionella spp.	*L. pneumophila*	Respiratory illness (pneumonia, Pontiac fever)
Mycobacteria (non-tuberculous)	*M. avium complex*	Respiratory illness (hypersensitivity pneumonitis), skin infections
Salmonella Typhi		Typhoid
Other *Salmonella*	*S. enterica, S. bongori*	Gastroenteritis, reactive arthritis
Shigella	*S. dysenteriae*	Dysentery
Vibrio cholerae	*V. cholerae*	Cholera
Viruses		
Adenoviridae	Adenoviruses	Gastroenteritis, respiratory illness, eye infections
Astroviridae	Astroviruses	Gastroenteritis
Caliciviridae	Noroviruses, sapovirsus	Gastroenteritis
Hepeviridae	Hepatitis E virus	Infectious hepatitis
Picornaviridae	Enteroviruses	Gastroenteritis, respiratory illness, nervous disorders, myocarditis
	Parechoviruses	Gastroenteritis, respiratory illness
	Hepatitis A virus	Infectious hepatitis
Reoviridae	Rotavirus	Gastroenteritis
Protozoa		
Acanthamoeba	*A. culbertsoni*	Granulomatous amoebic encephalitis
Cryptosporidium	*C. hominis/parvum*	Gastroenteritis
Cyclospora	*C. cayetanensis*	Gastroenteritis
Entamoeba histolytica	*E. histolytica*	Amoebic dysentery
Giardia	*G. intestinalis*	Gastroenteritis
Naegleria fowleri	*N. fowleri*	Amoebic meningitis
Helminths		
Ascaris	*A. lumbricoides* (roundworm)	Abdominal pain, intestinal blockage
Taenia	*T. saginata* (tapeworm)	Abdominal pain
Trichuris	*T. trichura* (whipworm)	Abdominal pain, diarrhoea

Sources: Adapted from WHO (2006; 2017a).

Issues have also been raised about the potential for selection and development of antibiotic resistant microorganisms in treated wastewater (WHO, 2015c). Antibiotic resistant bacteria (ARB) and antibiotic resistance genes (ARG) are a substantial worldwide public health issue and concerns have also been raised about exposure to ARB and ARG in water (WHO, 2015c; Olivieri et al, 2016). However, as the level of treatment applied in potable reuse schemes will generally exceed that used in existing drinking-water treatment plants, after treatment, concentrations of ARB and ARG in potable reuse schemes are likely to be lower than those found in conventional drinking-water supplies (Olivieri et al, 2016).

Table 2.2 Indicative concentrations of microorganisms in untreated wastewater[a]

Pathogen	Numbers in untreated wastewater (per litre)
Bacteria	
Escherichia coli (indicators)	10^5–10^{10}
Enterococci (indicators)	10^6–10^7
Clostridium perfringens (indicators)	10^4–10^6
Campylobacter	<1–10^5
Salmonella	<1–10^6
Shigella	<1–10^4
Vibrio cholerae	<1–10^6
Viruses	
Adenoviridae (adenoviruses)	<1–10^4
Caliciviridae (noroviruses)	<1–10^6
Picornaviridae (enteroviruses)	<1–10^6
Reoviridae (rotaviruses)	<1–10^5
Somatic coliphage (indicators)	<1–10^9
F-RNA phage (indicators)	<1–10^7
Protozoa	
Cryptosporidium hominis/parvum	<1–10^5
Entamoeba histolytica	<1–10^2
Giardia intestinalis	<1–10^5
Helminths	
Ascaris lumbricoides	<1–10^3
Trichuris trichuria	<1–10^2

[a] The data shown is indicative and should be used with caution. Reported concentrations are highly variable and rely on different methods. For example, bacteria are usually detected using culture-based methods while virus concentrations can be determined using culture (e.g. adenovirus) or nucleic acid based methods (e.g. norovirus, rotavirus). The relationship between genome concentrations and infectivity is variable.
Sources: Adapted from NRMMC-EPHC-AHMC (2006–2009), WHO (2006; 2017a), Health Canada (2010), Soller et al (2015), Deere & Khan (2016).

2.2 Chemical hazards

Chemical hazards in wastewater can include a wide range of substances that are naturally occurring or of anthropogenic origin. They include industrial chemicals, chemicals used in households, chemicals excreted by people, and chemicals used or formed during wastewater and drinking-water treatment processes (Table 2.3). Depending on the type of chemical hazard, concentrations may range from <1 ng to mg per L (NRMMC-EPHC-NHMRC, 2008). Metals and inorganic chemicals are generally present in higher concentrations (µg to mg per L) while pharmaceuticals and personal care products, when detected, are generally present in lower concentrations (ng to µg per L). While the list of chemical hazards in wastewater can be broad, studies have shown that concentrations typically detected are well below those that would represent a risk to public health (Schwab et al, 2005; Snyder et al, 2008; NRMMC-EPHC-NHMRC, 2008; Bruce et al, 2010; Bull et al, 2011; WHO, 2012) (see Chapter 5).

Depending on the management and control of industrial discharges, wastewater can have significant industrially related chemical contributions. There are millions of chemical formulations available commercially and the number of chemicals synthesized has grown tremendously over the past few decades (Snyder, 2014). Although only a small proportion of these chemicals will be in commercial or industrial use at any one time, the nature of municipal wastewater systems dictates that nearly all commercial products in use have some propensity to be collected and delivered to municipal WWTPs. Hence, wastewater can present a continually evolving composition of chemicals in complex mixtures. It is likely that chemical constituents will vary widely among regions depending on local circumstances and industrial activities. Industrial discharges can be a source of heavy metals, synthetic industrial chemicals, manufactured pesticides and pharmaceuticals, volatile organic carbons (VOCs), dioxins and polychlorinated biphenyls (PCBs) (Table 2.3).

Table 2.3 Chemicals potentially present in wastewater or produced during treatment

Type of chemical	Examples	Potential sources
Heavy metals	Cadmium, copper, chromium, lead, mercury, nickel, silver, arsenic (metalloid)	Industrial discharges, natural sources, water/wastewater, pipes and fittings
Inorganic chemicals	Fluoride, nitrate, nitrite, ammonia	Mains water, natural sources, human waste
Synthetic industrial chemicals	Plasticizers, biocides, epoxy resins, degreasers, dyes, chelating agents, polymers, polyaromatic hydrocarbons, polychlorinated biphenyls, phthalates	Widespread commercial use, industrial discharges
Volatile organic compounds	Petrochemical products, industrial solvents, halogenated DBPs	Industrial discharges, mains water (e.g. trihalomethanes)
Pesticides	Household, garden and agricultural pesticides	Domestic, agricultural and industrial discharges
Pharmaceuticals	Non-steroidal anti-inflammatories, antibiotics, anti-hypertensives, statins, veterinary pharmaceuticals	Pharmaceuticals and metabolites excreted by people and animals, domestic disposal of unused pharmaceuticals, discharges from manufacturing sites
Steroidal hormones (estrogenic and androgenic)	Estradiol, estrone, estradiols, testosterone	Human and animal waste (particularly from feedlots); can include excretion of natural hormones and contraceptive medication
Personal care products	Fragrances, cosmetics, antiperspirants, moisturizers, soaps, creams, whitening agents, dyes and shampoos	Human waste
Antiseptics	Triclosan, triclocarban	Household use and commercial use
Per- and polyfluoroalkyl substances	Perfluorooctanoic acid, perfluorooctane sulfonate	Household products (e.g. water and stain resistant compounds including furnishings and non-stick coatings for cookware), firefighting foams
Flame retardants	Brominated flame retardants, fyrol FR 2 (tri(dichlorisopropyl) phosphate), tris(2-chloroethyl) phosphate	Household products, e.g. furnishings, clothing, electrical devices
Dioxins and polychlorinated biphenyls	Octachlorodibenzo-p-dioxin, 2,3',4,4',5-pentachlorobiphenyl	Industrial discharges
Nanomaterials	Silver, titanium oxide, zinc oxides	Used in consumer products, e.g. personal care products, food storage containers, cleaning supplies, bandages, clothing and detergents
Cyanobacterial toxins	Microcystin, cylindrospermopsin, anatoxins, saxitoxins	Growth of cyanobacteria in wastewater treatment plants, wastewater lagoons and surface waters used as environmental buffers
Disinfection by-products	Trihalomethanes, haloacetic acids, bromate, chlorate, chlorite, *N*-nitrosodimethylamine	Reaction between disinfectants and organic material in wastewater and drinking-water; types produced dependant on source water and nature of disinfectant

Sources: NRMMC-EPHC-NHMRC (2008), NRC (2012), USEPA (2012), TWDB (2015), WHO (2017a).

Domestic waste can also be a source of a wide range of chemical hazards, including, those in faecal material and laundry, and kitchen and bathroom discharges. These can include pharmaceuticals and their metabolites, natural steroidal hormones, personal care products such as soaps, insect repellents, detergents, cleaning products, veterinary products used for pet care and antiseptics. Domestic waste can also be a source of chemicals from disposal of excess products, including paints, oils, garden pesticides and unused pharmaceuticals. Some countries have established programmes to reduce disposal of excess chemicals (USEPA, 2016; WHO, 2012).

Algal toxins such as microcystins, nodularins, cylindrospermopsin, anatoxins and saxitoxins are all naturally produced by freshwater cyanobacteria (blue-green algae); some of the toxins are hepatotoxic (microcystins, cylindrospermopsins and nodularins) while others are neurotoxic (anatoxins and saxitoxins). Under suitable conditions, cyanobacteria may grow, and possibly produce toxins in wastewaters, wastewater storages (e.g. lagoons) or in surface water bodies used as environmental buffers.

Disinfection by-products are formed by reactions between disinfectants and organic and inorganic constituents of water and are commonly produced at traditional drinking-water treatment plants. High initial concentrations of organic components, ammonia, bromide or iodide in wastewater may lead to elevated production of various, and sometimes unique, DBPs in potable reuse schemes. The nature and concentrations of DBPs will be influenced by:

- Nitrification at the WWTP and the efficacy of treatment processes in removing organic compounds prior to disinfection (Krasner et al, 2009).
- Wastewater possibly containing elevated concentrations of bromide and iodide leading to different DPB formation patterns compared with typical groundwaters or surface waters used as sources of drinking-water.
- The types of disinfectant used and various process parameters (e.g. temperature, pH, detention times in distribution systems). Formation of *N*-nitrosodimethylamine (NDMA) has been identified as a greater issue when chloramination is a final disinfectant (Sgroi et al, 2015). Bromate, brominated DBPs and iodinated DBPs can be produced by oxidation of bromide and iodide; chlorate and chlorite can be formed by decomposition of hypochlorite and can be produced from use of chlorine dioxide (Krasner, 2009).

In comparison to chemical disinfectants the production of DBPs from UV disinfection is less well established, but will depend upon factors such as the UV dose and the production of secondary oxidative species, such as hydroxyl radicals, which may catalyse chemical transformations within the water matrix.

Emerging chemicals/materials of concern include per- and polyfluoroalkyl substances and nanoparticles. Per- and polyfluoroalkyl substances are persistent and some are highly water soluble. They are used in the production of water-resistant and stain-resistant products, including furniture fabrics, cookware and clothing, as well as in fire fighting foams. They also arise from the breakdown of fluorotelomer alcohols, which are widely used in consumer products such as greaseproof food wrappers and stain-resistant carpet treatments. Perfluorinated residues (predominantly perfluorooctanoic acid, perfluorooctane sulfonate) have been detected in treated wastewater (Zareitalabad et al, 2013).

Nanomaterials are defined as natural or manufactured materials containing particles where one or more external dimensions range in size between 1 and 100 nanometres (European Union, 2011; Water Research Australia, 2013). The toxicological concerns for nanoparticles are related not only to their chemical composition, but also to their physical parameters, including particle size, shape, surface area, surface chemistry, porosity, aggregation and homogeneity of dispersions. As such, traditional techniques used for toxicological and eco-toxicological evaluation of chemical substances are not readily applied to the evaluation of nanoparticles (Hussain et al, 2009). Airborne exposures are the predominant risk concerns. There is limited knowledge about risks associated with waterborne exposures (Hussain et al, 2009; Neale et al, 2012).

2.3 Radiological hazards

Radionuclides are a category of contaminants that can be present in wastewater. Radionuclides are elements or isotopes whose nuclei spontaneously disintegrate to release alpha particles (helium nuclei), beta particles (electrons) or high energy gamma radiation; some produce more than one type of emission. Exposure to radiation may increase the long-term incidence of cancer.

Occurrence, fate and transport of radionuclides are reasonably well understood. Most radionuclides are naturally occurring and estimates of worldwide average annual exposures to radiation from cosmic rays, terrestrial radiation, inhalation, food and drinking-water are about 2.4 mSv and the typical average dose is 1 to 13 mSv. The dominant source of radiation is inhalation of radon (UNSCEAR, 2008).

Potential sources of radionuclides in wastewater include nuclear power plants and other facilities that use radioactive material for manufacturing. Such radionuclide releases are usually tightly regulated and exposures from artificial sources are minimal relative to natural background radiation. Medical facilities and patients discharging clinically used radionuclides can also be a source. Medical applications for radioisotopes include iodine-131 (half-life ~8 days) contrast media and technetium-99m (half-life ~6 hours). The short half-lives reduce persistence of these radioisotopes following shedding from out-patients or patients discharged from hospitals. Discharges from medical facilities to wastewater systems should be prevented.

Standard treatment technologies and processes used in potable reuse are effective in removing radionuclides.

2.4 Acceptability aspects – taste, odour and appearance

Acceptability aspects for other drinking-water sources are also applicable to potable reuse (WHO, 2017a, Chapter 10). However, some aesthetic issues are of particular relevance for potable reuse schemes due to source water quality, treatment processes and potential impacts on distribution systems due to blending. Wastewater is highly turbid and typically contains large numbers of compounds that can cause unacceptable tastes and odours. Treatment processes included in potable reuse schemes are effective in removing turbidity and taste and odour compounds.

Consumers generally assess the quality of their drinking-water by appearance, taste and odour rather than by reviewing physical, chemical and biological results. Therefore, appearance, taste and odour of drinking-water must be acceptable to generate and maintain public perception of high-quality water. Drinking-water produced by potable reuse schemes should match or exceed the acceptability characteristics of drinking-water from conventional local sources to maintain public confidence. Unacceptable appearance, taste or odour in drinking-water supply augmented with potable reuse will exacerbate consumer unease associated with its origin. Consumers may perceive that recycled water is not adequately treated to remove wastewater-derived contaminants if objectionable or variable taste, odours or colour are present, even when all health-based targets are met.

2.4.1 Taste and odour

Wastewater can contain a wide range of organic compounds that can give rise to odours ranging from ammonia to fishy and putrid, often at low concentrations (Burlingame et al, 2004; Suffet & Rosenfeld, 2007; Agus et al, 2011). Many wastewater-derived compounds have been extensively studied for their potential to produce nuisance odours (Burlingame et al, 2004; Agus et al, 2011). Common odour compounds or classes reported from WWTPs include hydrogen sulfide, organic sulfides (thiols), thiophenes, aldehydes, haloanisoles, halophenols, fatty acids and amines. In a well-operated municipal WWTP with aerobic processes, these odour compounds are typically removed from the liquid phase. Due to their relatively high volatility, a significant portion of wastewater-derived odorants are removed during open-air sedimentation, mixing and aeration. Many odorants, such as amines and alkyl acids, are biodegraded by microbes in activated sludge, trickling filters, biofilters or bioreactors. However, complete removal is not always achieved and in some cases odorants are detected in secondary wastewater at concentrations above odour thresholds (Agus et al, 2011).

While traditional wastewater treatment processes can reduce or remove many odour-producing chemicals, some aerobic and anaerobic biological processes employed for wastewater treatment may contribute to odours by transforming larger natural or anthropogenic organic materials into smaller organic compounds with odorous functional groups, e.g. alkyl acids, ketones or phenols. Wastewater processes such as trickling filters and activated sludge processes (ASPs) can support the growth of microorganisms including actinomycetes that produce geosmin and 2-methylisoborneol. These compounds produce earthy and musty/mouldy odours at very low concentrations (5–10 ng/L, Burlingame et al, 2004).

Treatment processes used in potable reuse that reduce organic contaminants such as soil-aquifer treatment (SAT), reverse osmosis (RO), activated carbon and advanced oxidation processes (AOPs) can reduce most wastewater odorants. While no single treatment process guarantees complete removal of taste and odour compounds from wastewater the combinations of processes typically used in potable reuse schemes should be effective.

The use of environmental buffers in IPR schemes may intensify or mitigate aesthetic concerns depending on the quality of the surface water source or characteristics of the aquifer. Blending in surface reservoirs and rivers will reduce volatile organic odorants by aeration but may introduce odour compounds such as geosmin and 2-methylisoborneol due to the occurrence of cyanobacteria.

Target concentrations have generally not been set for specific taste and odour compounds. In part this is due to the subjective nature of acceptability, local preferences and difference in sensory sensitivity which means that actual threshold concentrations and criteria for individual consumers can vary greatly. To determine acceptability of water supply augmented with recycled water, it is recommended that consumer satisfaction studies should be performed.

2.4.2 Colour and turbidity

Colour in domestic wastewater may range from light-brownish grey to black but it significantly diminishes to light yellow or light brown following secondary treatment (Metcalf & Eddy, 2003). Drinking-water containing colour at or below 15 true colour units is typically considered acceptable by consumers (WHO, 2017a). Treatment processes such as RO, advanced oxidation, ozone-biological activated carbon (ozone-BAC) and oxidizing disinfectants used in potable reuse schemes can all reduce colour to acceptable levels. While turbidity due to suspended solids in untreated wastewater is high, treatment processes used in potable reuse are very effective in reducing turbidity to below 0.1 nephelometric turbidity unit (NTU). Crystal clear water has a turbidity of <1 NTU; water does not become visibly cloudy until it reaches 4 NTU or above (WHO, 2017b).

Colour and turbidity can increase in distribution systems as a consequence of poor corrosion control, particularly when RO is included in the treatment train and the product water is not stabilized to reduce corrosion potential (Section 2.5.4).

2.4.3 Salinity

Salinity in wastewater depends on the initial salinity of the local mains water source and other factors such as intrusion of saline groundwater into sewerage systems. The palatability of water with a total dissolved solids (TDS) level of less than about 600 mg/L is generally considered to be good (WHO, 2017a). If TDS levels are significantly above 600 mg/L, they can be reduced by RO. Other processes such as media filtration, microfiltration (MF) or nanofiltration (NF) are not effective in the removal of salinity.

2.5 Control measures

Control measures should be applied from collection of wastewater to delivery of drinking-water to consumers. While treatment processes tend to be a focus of potable reuse schemes, other control measures designed to prevent contamination as close to the source as possible (e.g. industrial waste controls) are essential and should be included.

There are no prescriptive combinations of control measures that must be used in potable reuse schemes. The selection of control measures will often be influenced by existing infrastructure for wastewater and drinking-water treatment, established mechanisms to deal with industrial discharges, location (i.e. inland or coastal), availability of environmental buffers and regulatory specifications. For example, regulatory authorities may define a minimum number of treatment barriers (see Box 2.1). As a result, the treatment technologies and control measures employed can be quite diverse.

2.5.1 Source water protection

Source water for potable reuse schemes is wastewater which may contain domestic and commercial waste and, depending on design, industrial and stormwater contributions. In some situations, it may be possible to separate industrial and municipal waste streams. For example, in some locations, urban planning may allow heavy industries to be located away from catchments of WWTPs used as the source of a potable reuse facility (e.g. see Singapore Case Study, CS4).

In many cases, potable reuse schemes are developed as extensions of established municipal WWTPs. In these circumstances changing collection areas to reduce or eliminate industrial discharges may not be possible. However, control measures can be applied to reduce impacts of industrial discharges on wastewater quality. Waste discharge restrictions and pre-treatment requirements can significantly reduce the presence of chemical contaminants (Mosher et al, 2016). Controls on discharges of contaminants that either will adversely impact on the biological treatment processes in the WWTP or are not well removed by physical and chemical treatment processes will improve process efficiency and finished water quality. Many jurisdictions provide specific guidance on pre-treatment programmes for industrial dischargers (USEPA, 2011; WSAA, 2012). Community education programmes, such as those designed to reduce disposal of chemical wastes (e.g. unused paints, solvents and pharmaceuticals, etc.) via the sewerage system, may also have a beneficial impact on improving source water quality (WHO, 2012; USEPA, 2016).

It is also important to note that in many parts of the world, sewerage systems may be combined with urban drainage (stormwater primarily) and thus will be subjected to loading from urban runoff. Even in situations where stormwater is not intentionally combined, sewerage systems are generally not operated under pressure and can be subject to infiltration during rain events (Lee et al, 2015).

Organizations responsible for treating wastewater for subsequent potable reuse should undertake risk assessments to determine the range of contaminants that may be found in wastewater used as a source for potable reuse schemes. Such risk assessments should consider the sources of wastewater, including the range and number of industrial and commercial premises providing discharges. These risk assessments should inform the design of treatment/management plans.

Control measures to prevent contamination should also be applied where environmental buffers are used. These should take the form of normal catchment management activities to reduce spills, impacts of urban, industrial and agricultural discharges and growth of cyanobacteria in surface water bodies. Catchment management should also be applied to prevent contamination of groundwater.

2.5.2 Treatment

Following source water management, the next barriers to contamination are treatment technologies used to reduce concentrations of remaining microbial, chemical and radiological hazards to acceptable levels. Depending on established infrastructure, potable reuse schemes can include conventional WWTPs, advanced treatment plants and drinking-water treatment plants. All applied treatment processes should be considered as components of the potable reuse system. Different organizations may be responsible for operating the various treatment plants, hence coordination and communication will be essential to ensure consistent performance of the various components is maintained.

From a risk management perspective, the removal and disinfection of pathogens remain the most critical issues in the design of potable water reuse treatment trains since acute exposures can lead to immediate disease outbreak. Chemical contaminants with limited exceptions (e.g. copper and nitrate) are generally not considered acute threats but long-term chronic exposures may lead to adverse health outcomes.

As for all drinking-water supplies, ensuring safety is based on the use of multiple barriers, and in the case of potable reuse should consider the entire system from collection of wastewater to production and supply of drinking-water to consumers While this includes source water control, potable reuse schemes require multiple treatment barriers to ensure safety. In some cases, minimum numbers of barriers may be specified in policies or regulations (see Box 2.1). The selection of processes to include in a multiple-barrier treatment system should consider including a pre-determined level of redundancy tailored to the removal of microbial and chemical contaminants (see Section 2.5.5). This design principle has been followed in potable reuse schemes worldwide (Drewes & Khan, 2011; 2015). The multiple-barrier approach ensures that performance failure at a single barrier should not lead to significant failure to remove microbial or chemical contaminants. As such, the multiple-barrier approach may be most effective when processes with diverse modes of operation and removal mechanisms are employed (see Section 2.5.5).

Box 2.1 Multiple-barrier approach

In a 1975 report on potable reuse it was recommended that multiple-barrier treatment designs should ensure that each pollutant should be reduced in concentration by at least two, and preferably by three or more, processes (WHO, 1975). In line with this recommendation the DPR scheme in Windhoek, Namibia, was specifically designed to include multiple barriers (Du Pisani & Menge, 2013; Law et al, 2015). The treatment train includes seven treatment barriers to address:

- microbiological pollutants (three of the barriers)
- physical and organoleptic parameters (two of the barriers)
- trace organics and DBPs (four of the barriers)
- critical parameters with no public health risk (e.g. stability) (one barrier).

The Californian regulations for potable reuse specify that treatment trains for IPR must include at least three separate processes for each pathogen (CDPH, 2014).

The primary categories of treatment employed in potable reuse schemes are biological processes, physical separation (filtration and adsorption), chemical oxidation and disinfection processes. These processes are described below. Multiple combinations of these processes are possible, but, typically, advanced treatment processes such as membrane filtration, advanced oxidation and activated carbon follow a biological wastewater treatment process such as activated sludge or membrane bioreactor (MBR), which are primarily designed to remove organic matter, nutrients and some microbial pathogens. Subsequent advanced processes provide additional barriers to pathogens and chemical contaminants that might also result in reduction of salinity and nutrients (NRC, 2012). Some IPR schemes, such as the Montebello Forebay Scheme in Southern California, USA, rely on treatment systems such as SAT that combine multiple removal mechanisms (i.e. filtration, adsorption, biodegradation) using naturally based subsurface treatment systems (see Box 2.2). More recent designs have generally favoured ozonation, activated carbon adsorption, AOPs and low pressure membrane filtration (Drewes & Khan, 2011; 2015).

Communities in coastal regions have tended to adopt the type of treatment train developed by Orange County, USA (see Box 2.2), and similar schemes incorporating RO have been installed in Singapore, Australia and Europe. In the absence of ocean discharges, inland communities such as Windhoek, Namibia, have preferred non-RO based schemes and selected combinations of oxidation processes, activated carbon filtration, biofiltration and membrane filtration (see Box 2.2).

Box 2.2 Setting the scene: Pioneering potable reuse schemes

Montebello Forebay, United States of America: Potable reuse was first implemented in the 1960s using surface spreading followed by SAT, where wastewater after secondary treatment, chlorination and media filtration is infiltrated through the vadose zone into the aquifer at the Rio Hondo and San Gabriel Coast Spreading Grounds. The recharged groundwater blended with native groundwater is subsequently recovered, disinfected and fed into the drinking-water distribution system.

Orange County, United States of America: Potable reuse was introduced with development of Water Factory 21 in 1976. The scheme included injection of treated wastewater into a coastal aquifer. Water Factory 21 was replaced by the Groundwater Replenishment System in 2007. Following treatment by conventional biological wastewater processes, MF, RO, AOP (UV/H_2O_2), stabilization and final chlorination, wastewater is injected into the coastal aquifer to provide a seawater intrusion barrier and percolated from several lakes into groundwater used as a source of drinking-water that is often not chlorinated after withdrawal.

Windhoek, Namibia: The first DPR scheme was introduced in the 1960s. The current scheme combines biological treatment, ozonation, dissolved air flotation, media filtration, activated carbon adsorption and ultrafiltration (UF) of wastewater, with the product water blended with drinking-water produced from surface water/groundwater and fed into the drinking-water distribution system.

In practice, full-scale potable reuse schemes include a large variety of process combinations (Drewes & Khan, 2011; USEPA, 2012a; Gerrity et al, 2013b; Burgess, 2015; Onyango et al, 2015; Tchobanoglous et al, 2015). Figure 2.1 shows examples of potable water reuse schemes already in operation.

The selection of a treatment train for a specific potable reuse scheme must be carefully evaluated by each community. Irrespective of which treatment combination is selected, safety will depend on meeting health-based targets identified for microbial, chemical and radiological quality (Chapter 5) through application of multiple-barrier processes along with online or frequent operational monitoring to ensure consistent and reliable operation.

The design of potable reuse schemes needs to consider wastewater flows and loads as these can vary diurnally (Nelson et al, 2011), from day to day (Huerta-Fontela et al, 2008; Gerrity et al, 2011) and seasonally (Merel et al, 2015b).

Figure 2.1 Examples of potable reuse schemes

1 Secondary treatment usually based on activated sludge and in most examples includes nutrient reduction.
2 DWTP = drinking-water treatment plant.
3 UOSA = Upper Occoquan Service Authority.

Wastewater treatment

Initial treatment steps in potable reuse schemes typically involve traditional wastewater treatment processes. In many cases, potable reuse schemes retain existing WWTPs. Although possible, replacing existing WWTPs can increase the cost of potable reuse systems as well as presenting practical difficulties during construction. However, wastewater from established treatment plants may exhibit wide variability in quality depending on the types of processes in place and their management (Ort et al, 2010). Maintaining and optimizing effective wastewater treatment is extremely important for efficiency and efficacy of later advanced treatment processes. Where necessary, upgrades of existing plants should be considered to reduce variability and reduce the burden on subsequent treatment processes.

Wastewater treatment plants typically include primary and secondary treatment processes and may include advanced treatment (sometimes identified as tertiary treatment).

Primary treatment is essentially a physical treatment process which removes suspended solids. It removes some organic nitrogen, phosphorus and heavy metals but only provides limited removal of microbial pathogens.

Secondary treatment involves biological digestion and is commonly based on some form of ASP or trickling filters. It removes organic materials by digestion and should reduce biochemical oxygen demand and suspended solids by 85% or more (Metcalf & Eddy, 2003; Asano et al, 2007). Particle bound chemicals are removed and concentrations of microbial pathogens are reduced (see Section 2.6). Targeted nutrient reduction processes are often included in the design of ASPs, e.g. biological nutrient reduction (BNR). Nitrification and denitrification processes, in particular, can greatly improve water quality for downstream processes such as advanced oxidation and chlorination by removing ammonia and nitrate, respectively. Maintaining longer solids retention times in activated sludge based processes can provide attenuation of many trace organic contaminants (Clara et al, 2005; Gerrity et al, 2013a).

In recent years, secondary treatment has seen increased use of MBRs where membrane filtration (MF or UF) is integrated with biological treatment in the form of a suspended growth bioreactor. The membranes are used to reject solids generated by the biological process resulting in the production of clarified secondary effluent. The membrane filters provide enhanced removal of microbial pathogens with the extent of removal depending on pore size. This removal is enhanced by formation of a cake layer on the surface of membranes during operation, which effectively reduces pore sizes and increases removal of small particles such as viruses (Branch & Le-Clech, 2015).

Advanced treatment can include a range of processes of the type used in drinking-water treatment plants. These include oxidation, adsorption, media filtration, membrane filtration and disinfection and are discussed below.

Soil-aquifer treatment

From a technical point of view, perhaps the most basic and robust potable reuse treatment is groundwater infiltration, which is also known as SAT (Laws et al, 2011). Soil-aquifer treatment is a low technology process where treated wastewater percolates from spreading basins through soil which provides nutrient, microbial and chemical attenuation. Soil-aquifer treatment requires availability of unconfined aquifers, vadose zones with no constricting layers and soil that allows for infiltration while being fine enough to provide filtration. Subsequent aquifer storage also results in reduction of microbial pathogens and some chemical contaminants. While monitoring data show that viruses and bacteria are rapidly attenuated during SAT (Betancourt et al, 2014), some trace organic chemicals can be highly persistent and may not be well attenuated in this type of natural system (Snyder et al, 2004; Laws et al, 2011). In the Montebello Forebay of Los Angeles, USA, treated wastewater is infiltrated into the groundwater which is later harvested and disinfected with chlorine before direct distribution as potable water. The post-SAT water meets, or exceeds, all state and federal laws for drinking-water quality. Aquifer storage involving direct injection of treated wastewater into aquifers without soil infiltration is also used for potable reuse (see Case Study 5).

Oxidative processes

Many potable reuse treatment schemes utilize an oxidative process for attenuation of organic contaminants. The most common oxidative processes, ozonation and AOP, can be extremely effective but by-product formation must be carefully monitored and controlled. Operational and energy costs are high. Advanced oxidation processes enhance degradation of chemical contaminants through increased production of hydroxyl radicals from hydrogen peroxide (H_2O_2) and UV light or ozone and UV light. Advanced oxidation is effective against a wider range of organic chemicals and at higher reaction rates than standard oxidation processes (Kommineni et al, 2000; Wang & Xu, 2012).

Using processes such as biological active carbon (BAC) following oxidative processes can be very effective for reducing many organic transformation compounds produced by the oxidation step, although some substances such as bromate are generally not effectively removed (Asami et al, 1999). In addition to providing attenuation of organic chemicals, AOPs also provide high levels of microbial pathogen inactivation (Section 2.6).

Activated carbon adsorption

Adsorptive activated carbon can remove the vast majority of organic contaminants. However, breakthrough from the activated carbon can occur as a function of molecular structure or contaminants, water quality, the type of activated carbon, and the operational parameters employed (Snyder et al, 2007; Redding et al, 2009; Anumol et al, 2015). The use of activated carbon can be relatively expensive and will require periodic replacement or reactivation. Activated carbon also can serve as a support structure for the growth and retention of biological organisms resulting in formation of BAC which may be operated as a stand-alone process or preceding absorptive granular activated carbon (GAC). While adsorptive removal of dissolved organic carbon (DOC) by BAC deteriorates over time, the removal of biodegradable DOC increases and is maintained for many years (Pipe-Martin et al, 2010; Rattier et al, 2012).

Media filtration

Media filtration is one of the most common treatment processes used to remove particles and associated microbial pathogens from sources of drinking-water. Media filtration includes slow sand, rapid sand, granular or dual media filters using materials such as sand and anthracite. Filters act to remove suspended solids from source waters. Coagulation, flocculation and sedimentation are often used immediately prior to media filtration to enhance particle removal. As an alternative to sedimentation, dissolved air flotation can be used to remove flocs using fine air bubbles which float particles to the surface of tanks where they can be removed by skimming. Particles trapped by media filtration are removed by taking filters out of service and backwashing them to dislodge and discharge trapped particles. Media filtration needs careful management and monitoring to maintain optimum performance. Particular care needs to be taken at the end of filter runs, during return to service following backwash and at start up following interruptions to use. Incorporating filter to waste for a short period following backwash can reduce the possibility of poor performance. Media filtration provides an effective barrier to protozoa and to a lesser extent viruses and bacteria (USEPA, 2005).

Low pressure membrane filtration

Low pressure membrane filtration includes MF and UF with pore sizes ranging from 0.1–0.2 microns for MF to 0.01–0.05 microns or less for UF (USEPA, 2005) (Figure 2.2). Membranes are typically manufactured as flat sheets or hollow fibres using synthetic polymers and remove particles primarily by size exclusion although electrostatic repulsion and adsorption can play a role (USEPA, 2005). Filtration can be improved by formation of a cake layer fouling on the surface of membranes during operation which effectively reduces pore sizes and increases removal of small particles such as viruses.

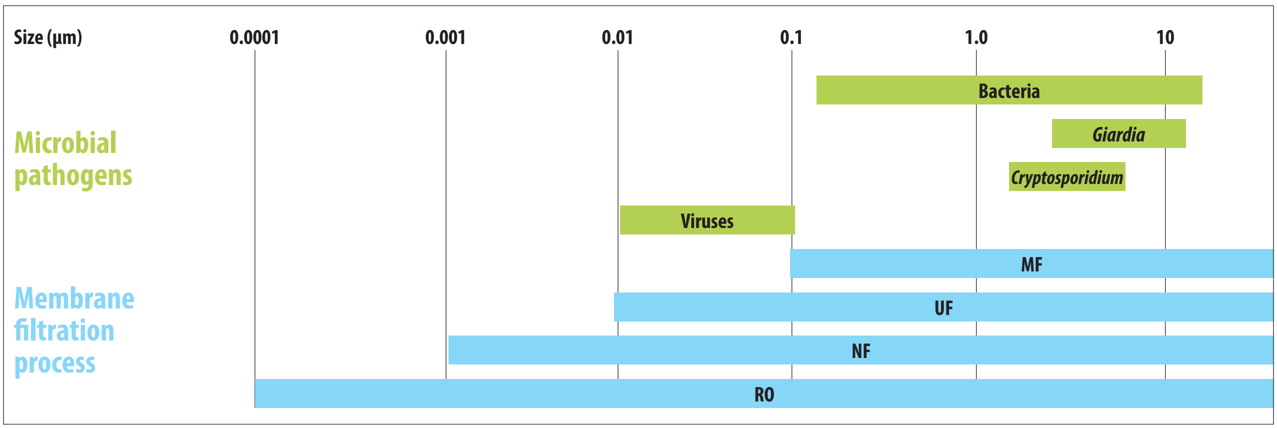
Membrane filtration is being used with increasing frequency in drinking-water and wastewater reuse schemes as effective barriers for pathogenic protozoa and to a lesser extent the smaller viral pathogens (USEPA, 2005). In potable reuse schemes membrane filtration can be used to provide consistently low turbidity water that reduces fouling of subsequent processes such as NF and RO.

Ceramic filters which also remove microbial pathogens by size exclusion are attracting increased interest as alternatives to membrane filters (Duke, 2014). They have a higher capital cost but operate at lower pressures and are longer lasting.

High pressure membrane filtration

High pressure desalting membranes such as RO and NF are extremely effective physical barriers for all pathogens and most organic contaminants (Bellona et al, 2008). Most RO membranes can remove upwards of 99% of salinity from water and hence are expected to provide an even greater removal of microbial contaminants (Figure 2.2). Nanofiltration is not as effective in removing salinity but will remove substantial amounts of higher valent ions like calcium, magnesium and sulfate. While highly effective in removing organic contaminants, some non-polar, low molecular weight organics, such as NDMA and 1,4-dioxane, can pass through RO membranes (Drewes et al, 2005). A major challenge for operation of desalting membranes is the loss of water in the form of a concentrated brine stream, which often contains up to 20% of the original water flow and rejected salt and organic chemicals at elevated concentrations. For coastal communities, the brine stream is often discharged into the marine environment but inland communities may find brine disposal challenging. Desalting membrane processes are relatively expensive to operate because of the high pressures needed and associated energy costs.

Figure 2.2 Membrane filtration pore sizes



Source: Adapted from USEPA (2005).

Disinfection

Potable reuse schemes invariably include disinfection processes to inactivate microbial pathogens, including bacteria, viruses, protozoa and helminths. Disinfection can also be applied within treatment trains to reduce biofouling primarily by bacteria (e.g. of membranes) and within distribution systems to reduce biological growth and to provide protection of water quality in the event of ingress of contamination (e.g. through mains breaks).

While biological processes (e.g. secondary treatment), natural systems (e.g. SAT) and physical barriers (e.g. MF, UF, NF and RO) all provide removal of microorganisms, disinfection generally refers to agents used to inactivate microbial pathogens (i.e. disinfectants). The most common disinfectants used in drinking-water and wastewater treatment are oxidizing chemicals such as chlorine, chloramines, ozone and chlorine dioxide and UV light irradiation. These have different impacts against the various groups of pathogens, for example UV light is very effective in low doses against *Cryptosporidium* and *Giardia* but much higher doses are required to inactivate viruses (Hijnen et al, 2006; USEPA, 2006b). Similarly, chlorine is effective against pathogenic bacteria and viruses, can inactivate *Giardia* at higher Ct values[3] but has limited impact on *Cryptosporidium*. As described in Chapter 5, performance targets are normally defined for a small number of reference pathogens. This approach also applies to assessing effectiveness of disinfection where abundant, resilient organisms are generally selected as indicator pathogens. For example, the effectiveness of UV light in disinfecting pathogenic viruses is typically based on inactivation of adenovirus which is relatively resistant to UV light (USEPA, 2006b). It is then assumed that by ensuring effective inactivation of adenoviruses that less resilient viruses will be inactivated at least at the same level.

While effective disinfection is fundamentally important for potable reuse, many processes can lead to the production of undesirable and potentially hazardous DBPs. The type and concentrations of DBPs formed depend on a number of factors, including source water composition, treatment processes and the method of disinfection (see Section 2.2) (Krasner et al, 2009). It is important to note that DBP formation and control occur not only at the potable reuse treatment plant but also extend into the distribution system where blended water may further impact formation potential.

The control of DBP production can be achieved by minimizing the presence of DBP-precursors using treatment processes that reduce total organic carbon (TOC) concentrations before disinfection and optimizing disinfection processes. Selection of disinfection processes can also reduce DBP production (e.g. chloramination rather than chlorination for control of microbial quality in distribution systems). In addition, some DBPs can be removed by subsequent treatment processes within the treatment plant or by the environmental buffer, if used. While treatment trains should be designed to minimize formation of DBPs, an important tenet for all drinking-water supplies, including potable reuse schemes, is that disinfection takes priority and should not be compromised in attempting to meet DBP targets (WHO, 2017a).

2.5.3 Environmental buffers and engineered storages

A key element of IPR is an environmental buffer. The environmental buffer, either an aquifer or a surface water reservoir, provides a number of potential benefits, including contaminant attenuation, dilution and blending, and time to detect and respond to failures before final treatment and distribution. Environmental buffers also provide storage capacity to hold water during periods when production exceeds demand. Public acceptance may also be improved by the use of an environmental buffer which provides a sense of natural assimilation for the treated wastewater and a physical or temporal separation between the production of treated wastewater and delivery of drinking-water.

Validation of contaminant removal by environmental buffers can be challenging and generally needs to be done on a case-by-case basis (Section 2.6). Removal of microbial pathogens has been demonstrated as a function of retention times in groundwater storages (Pang, 2009; NRC, 2012; Betancourt et al, 2014).

While environmental barriers can provide advantages, there are also potential challenges and disadvantages that need to be addressed including:

- In some locations establishing an environmental buffer can be challenging due to the lack of local surface water reservoirs or accessible aquifers. There may also be regulatory restrictions on discharging and storing treated wastewater in existing water resources.

[3] Ct values are calculated from the product of disinfectant concentration (mg/L) and time (minutes).

- Pumping water into and out of groundwater basins or pumping water long distances to surface water reservoirs can be expensive and energy intensive (ATSE, 2013).
- Water quality in environmental buffers can influence suitability for use in potable reuse schemes. Adding treated wastewater to an environmental buffer may dilute residual contaminants such as microbial pathogens or trace organic chemicals remaining after treatment. Conversely the addition of highly treated wastewater may dilute contaminants present in the environmental buffer but this will reduce the quality of the treated wastewater. For example, surface water can contain natural organic matter, microbial pathogens, cyanobacterial toxins and pesticides while groundwater can contain naturally occurring hazards such as arsenic, fluoride, selenium and nitrates. Potential impacts of environmental buffers on water quality need to be assessed as part of developing WSPs for potable reuse schemes. Conventional drinking-water treatment (filtration and disinfection) is typically applied when surface water is used as an environmental buffer.

For DPR schemes the environmental buffer is eliminated and mechanisms to compensate for the associated loss of contaminant attenuation, dilution and time benefits (for monitoring and responding to treatment failures) should be considered. Contaminant attenuation can be readily replaced with traditional treatment barriers. Hence, the key considerations are how to effectively replace monitoring and response time benefits attributed to environmental buffers. One mechanism that can be applied is an ESB. An ESB is a storage basin or system that provides sufficient time, termed the failure and response time, to interrogate and respond to any faults, including exceedances of critical limits in operational monitoring of the treatment train. Storage times in ESBs are likely to be of the order of hours to days. The failure and response time should take into account sampling intervals, time to complete analyses and time to respond. For example, for online parameters such as turbidity or disinfectant residuals, sampling intervals are very short, analyses are completed immediately and actions can be implemented within minutes. This can involve interrogating system performance by an operator or making a decision to stop the supply of water. Monitoring intervals for other tests such as pressure decay testing of membranes may be undertaken daily, extending the failure and response time. Due to practical constraints, it is unlikely that ESBs will provide sufficient failure and response time for chemical contaminants that require more complex analyses and generally have long analytical turnaround times. This is not considered a significant issue since responding to exceedances of chemical guideline values is generally not time sensitive. Risks generally occur only after long-term exposure to concentrations consistently exceeding guideline values.

Configurations for an ESB can include plug-flow pipelines, baffled tanks or tanks in parallel, operated in a fill, storage and draw mode. The latter approach, using three or more tanks in alternating fill, storage and draw mode is the simplest. The ESB concept can also be employed in both IPR and DPR treatment schemes, as part of a final treatment step to ensure disinfectant Ct values are achieved or to provide buffering storages to maintain supply during short-term peak demands that exceed normal production capacities. This type of use is relatively common in traditional drinking-water systems. Potable reuse schemes at Beaufort West, South Africa, and Big Spring, USA, both include ESBs (ATSE, 2013).

2.5.4 Blending, storage and distribution

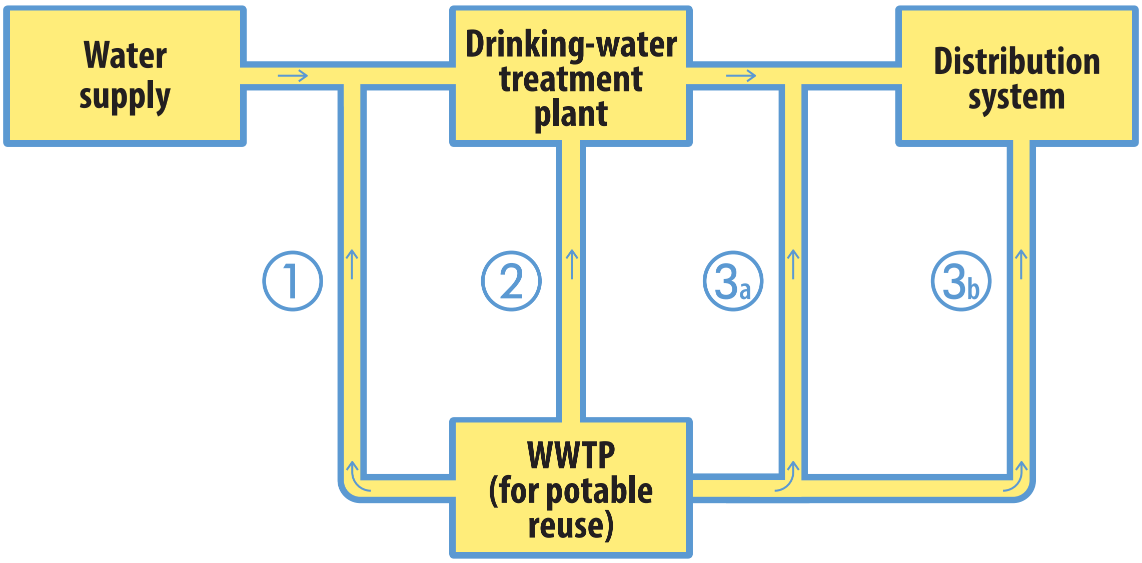
From a practical perspective, incorporating potable reuse into a water supply portfolio faces many of the same challenges as selecting and blending any other new water source such as groundwater, surface water or desalinated seawater into an existing system. Potable reuse water can conceivably be blended into the water supply at three main locations in a drinking-water treatment/distribution system (Figure 2.3), including within the:

- source water before the drinking-water treatment plant (1)
- drinking-water treatment plant prior to distribution (2)
- potable water distribution system (3).

Blending requires a high level of operational control, appropriately sized storage and mixing zones, and a firm understanding of the potential impacts on process performance and distribution system stability/quality, to ensure any upstream process upsets can be addressed in a timely manner and to maintain public confidence in the system. These issues are not unique to potable reuse, and potential water quality and distribution system impacts from drinking-water source blending have been studied extensively leading to the development of multiple tools and recommendations for managing blended water quality (Install & Zeilig, 2007; Peet et al, 2001; Taylor et al, 2005; 2008; Duranceau et al, 2011).

Water from potable reuse schemes must be evaluated for corrosion potential and DBP formation, similar to conventional water treatment systems. High purity water can pose unique challenges, especially if the water has been purified with RO treatment to produce very low ionic strength water. Reverse osmosis product water requires stabilization with added minerals to raise alkalinity and pH to achieve a positive Langelier saturation index, or an appropriate calcium carbonate precipitation potential or aggressive index to prevent erosion or corrosion of pipeline and reservoir materials. Stabilization can be accomplished by mineral addition post treatment or by blending treated water with other sources of waters with naturally higher mineral content or alkalinity. Without proper stabilization, treated wastewater produced by processes incorporating RO will be aggressive to cement mortar lined pipeline materials or concrete tanks and corrosive to metal pipeline and tank materials and components such as valves and backflow prevention devices, the distribution system and household plumbing (e.g. copper and lead). If water from potable reuse schemes is not stabilized prior to storage and distribution, alternative materials will need to be selected to reduce the potential for corrosion damage. For example, high-density polyethylene pipeline materials and properly cured epoxy coatings in reservoirs can be used to withstand the more aggressive waters without corrosion, erosion or leaching.

Figure 2.3 Possible blending locations of potable reuse water



Blended waters may contain different DBP precursors. Depending on the modes of disinfection this may result in different combinations and concentrations of DBPs. For example, formation of NDMA could be an issue, particularly if chloramination is used as a residual disinfectant in blended water (Krasner et al, 2009; Sgroi et al, 2016).

Bench-scale testing should be undertaken to assess the impact of blending on drinking-water quality on treatment processes (where blending occurs upstream of final drinking-water treatment plants), corrosion control and DBP production (Tchobanoglous et al, 2015).

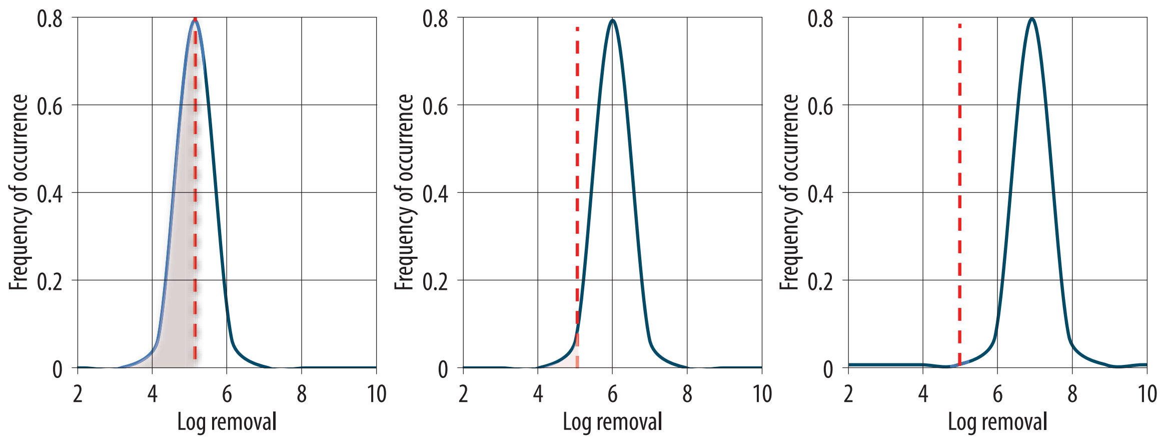
Blending can also be an issue in environmental buffers. The chemistry of purified waters introduced into groundwater aquifers must be managed with an awareness of any potential for mobilization of naturally occurring elements such as arsenic. Addition of minerals such as magnesium and calcium can help mitigate the risk of arsenic mobilization. Control of pH and redox potential may also be necessary to avoid mobilizing elements such as arsenic or hexavalent chromium from the aquifer geology.

2.5.5 Reliability, redundancy, robustness and resilience

Reliability can be achieved through the concepts of redundancy, robustness and resiliency (Pecson et al, 2015). Reliability is a widely used term, which points to the attribute of consistently meeting goals. For public utilities reliability is often associated with consistency in providing service. For potable reuse systems, reliability is used to describe the ability of the system to provide water that consistently meets the public health protection provided by existing drinking-water supplies. Redundancy, robustness and resiliency describe the measures, which can be taken to ensure this kind of reliability.

Redundancy is about the use of measures beyond minimum requirements to ensure that treatment goals are more reliably met or that performance can be more reliably demonstrated. A common kind of redundancy used in the water industry is the provision of a standby pump or filter to ensure that water can more reliably be provided at a facility's design capacity. As important as this kind of reliability is, it is different from the reliability provided when additional treatment is included above that required to meet removal targets. The traditional concept of providing multiple barriers of treatment generally describes this kind of redundancy. The benefits of providing redundancy in treatment for pathogen inactivation or removal for a process train seeking to meet a 5-log reduction goal are illustrated in Figure 2.4. Three process trains are compared, which are designed to seek a median performance of 5-, 6- and 7-log reduction, each with the same precision. The probability that their performance will fall below the 5-log reduction goal rapidly diminishes as additional redundancy in reduction is designed into the process. Increasingly, credit for performance goals is not achieved unless there is confirmation through operational monitoring that critical control measures are performing (see Section 2.6). As a consequence, there are circumstances when redundancy in monitoring can also support greater reliability.

Figure 2.4 Benefits of redundancy in treatment



Median 5-log
≤5-log 50% of the time

Median 6-log
≤5-log 2.3% of the time

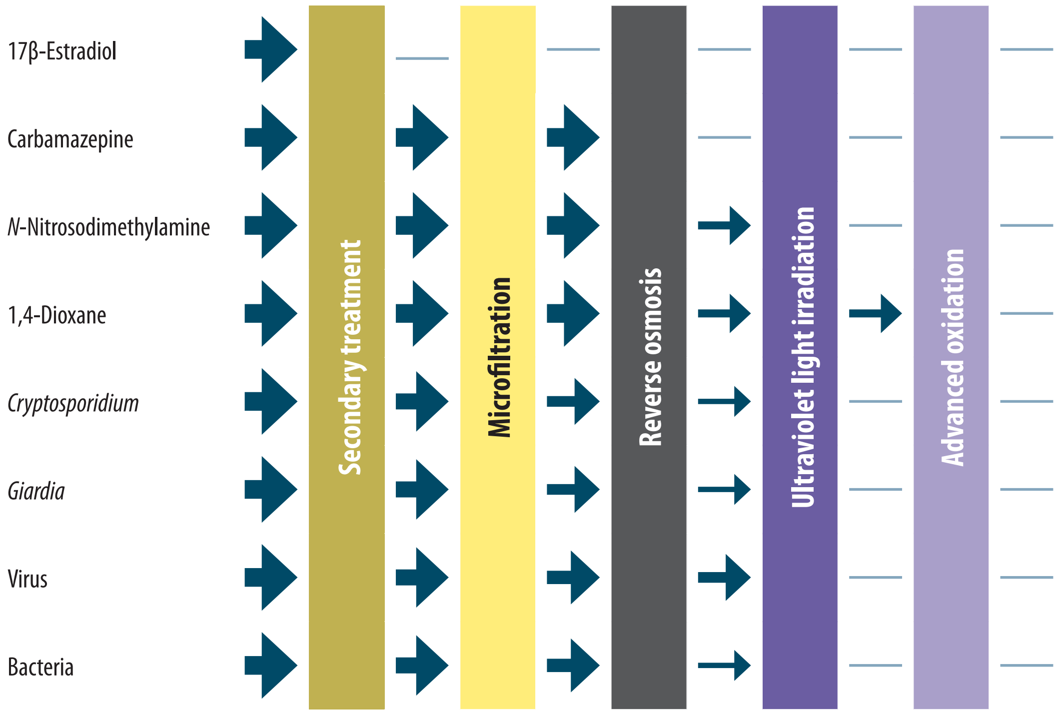
Median 7-log
≤5-log 0.03% of the time

Note: Adding treatment to provide higher median log reductions increases the likelihood that the performance target (5-log reduction) will be achieved.

Robustness refers to the ability of the system to address a broad variety of contaminants and resist catastrophic failures. The use of multiple barriers of treatment will generally make a train of processes more robust than a single process even when both the multiple-barrier train and the single process are designed to meet the same treatment goal (with no redundancy). The multiple-barrier train exhibits greater resistance to partial or catastrophic failure, including the unlikely occurrence of simultaneous failure of independent barriers (Pecson et al, 2015).

The elements of a multiple-barrier treatment train can also provide another kind of robustness increasing the breadth of contaminants that the train is able to successfully address. This concept is illustrated in Figure 2.5 for a process train with secondary wastewater treatment, MF, RO and AOP (UV/H_2O_2). In this process train, a number of typical treatment barriers to both pathogens and chemical contaminants are included with the degree of removal of selected organic and microbial contaminants illustrated by the reduction in the width of the arrows. The AOP (UV/H_2O_2) is broken into two parts to illustrate the unique role of UV. The lack of an arrow means that targets have been achieved.

Figure 2.5 Benefits of a multiple-barrier treatment train in providing robustness regarding contaminant removal



Source: Adapted from Pecson et al (2015).

Resilience is about ensuring reliability when redundancy and robustness are not enough. Provisions need to be made to respond and adapt to incidents and events (see Chapter 4). One example is the combination of monitoring control measures within treatment trains and use of ESBs. If operational criteria are not met, immediate remedial action can be implemented or the water diverted to alternate uses. ESBs provide time to stop supply before the water is delivered to consumers.

2.6 Validation of control measures

Control measures used in potable reuse schemes need to be validated to demonstrate that individual processes will meet performance targets and collectively, will consistently and reliably produce safe drinking-water and ensure that public health is protected. Although this is no different from other sources of drinking-water, the broader range of chemical contaminants and relatively high concentrations of microbial pathogens in untreated wastewater can increase the focus on validating performance.

Validation is the process of obtaining evidence that selected control measures will be effective in achieving specified levels of hazard reduction. It also defines the operational criteria required to ensure that the control measures continue to function effectively (Bartram et al, 2009; 2017a). It is an intensive activity undertaken over a limited period of time and is an essential input into selection of treatment processes by drinking-water suppliers and approval of WSPs by regulatory authorities. Validation can take three basic forms:

- evaluation of existing data and information such as published data and manufacturer conducted challenge studies;
- evaluation of results from process specific certification schemes;
- on-site testing of pilot-scale processes or full-scale systems.

For some treatment technologies such as UV light disinfection and membrane filtration, standards and protocols have been established for validating performance (ÖNORM, 2001; 2003; USEPA, 2005; 2006b; DVGW, 2006; WaterVal, 2016a; 2016b; 2016c). Certification against these standards and protocols can be used providing it is relevant to the characteristics of the water to be treated. For example, certification of UV light technology is typically only valid for specified ranges of transmissivities.

On-site testing of full-scale systems is usually undertaken as part of pre-commissioning or commissioning of potable reuse schemes. An important constraint of on-site testing is that demonstrated pathogen reductions are often limited by the range of concentrations of microbial pathogens or surrogates present in feedwater. On-site testing needs to be performed under the range of conditions that are expected to occur during the life of the potable reuse scheme. This includes variations in water quality and flow. Validation only applies within the defined windows of water quality and flow. On-site testing should consider the effectiveness of control measures in dealing with system specific contaminants of concern. Validation does not apply when design capacity of processes is exceeded. Pilot testing can also be used but only when there is certainty that results are directly applicable and are scalable to full size plants and schemes.

The first component of validation is demonstrating the removal of microbial hazards by control measures which is usually performed using challenge tests (USEPA, 2005; Department of Health, State of Victoria, 2013). The most direct approach is to measure $\log_{10}$ reduction values[4] (LRVs) of reference pathogens achieved by treatment processes (e.g. *Cryptosporidium* for protozoa). Alternatively, surrogate organisms (e.g. *E. coli* for bacteria, coliphages for viruses and *Clostridium perfringens* or *Bacillus subtilis* spores for protozoa) can also be used provided a correlation or conservative relationship with the reference pathogens is established for the process being validated (USEPA, 2005; Department of Health, State of Victoria, 2013). Table 2.4 provides a summary of validated LRVs demonstrated by challenge testing ($LRV_{C\text{-test}}$) for a range of indicative treatment processes commonly used in potable reuse schemes.

The second component of validation is identifying operational criteria that can be used to demonstrate ongoing performance of control measures. Operational monitoring parameters are required to ensure that any deviation from required performance is detected in a timely fashion (see Section 3.1). In the case of disinfection processes this is relatively straightforward; pathogen LRVs are based on transmitted UV doses or disinfectant Ct values which can be operationally monitored online (USEPA, 2003; Hijnen et al, 2006; Keegan et al, 2012; USEPA, 2006b). However, for processes that provide physical removal of pathogens (e.g. MBR, low pressure membrane filtration and RO) the relationship between removal capability and operational monitoring parameters is not as direct. Testing of operational parameters used to monitor these processes typically lacks the sensitivity of tests for pathogen removal (USEPA, 2005; Department of Health, State of Victoria, 2013). For example, membrane filtration processes can be shown to achieve pathogen LRVs of 6 or more in challenge testing but turbidity removal is limited to a sensitivity of 1.5–2.0 logs (USEPA, 2005; Department of Health, State of Victoria, 2013; TWDB, 2015). Direct integrity testing of membrane filters can be used to demonstrate an LRV sensitivity of 4 logs (USEPA, 2005; TWDB, 2015). Operational monitoring sensitivity is typically included in established validation protocols (USEPA, 2005; WaterVal, 2016a; 2016b; 2016c). In these protocols the validated LRVs attributed to a technology are the lower of those demonstrated by challenge testing and those from challenge testing after consideration of operational monitoring sensitivity.

Table 2.4 provides a summary of validated pathogen LRVs for indicative treatment processes, taking into account the sensitivity of operational monitoring in addition to the results from laboratory or field-based challenge testing (LRV_{OMS}). Generally, the LRV_{OMS} should be adopted in designing potable reuse schemes. This is consistent with the reliance in WSPs on the use of operational monitoring to demonstrate ongoing performance of control measures. However, proponents of potable reuse schemes, in consultation with regulators and other stakeholders, can choose whether validated LRVs based on results from challenge testing are used with or without considering the sensitivity of operational monitoring (i.e. $LRV_{C\text{-test}}$ or LRV_{OMS}).

In the case of chemical hazards, removal can be linked to operational monitoring of selected surrogates and indicators (Drewes et al, 2008; Dickenson et al, 2009) (see Section 3.3). For example, TOC can be used as an operational parameter to monitor general removal of chemical hazards by RO. Discrete chemical species that may or may not be of direct public health relevance can also be used as operational indicators of treatment performance (Dickenson et al, 2009). For instance, the artificial sweetener sucralose can be applied as an indicator of treatment process efficacy since it is relatively resilient to oxidation and biological processes, yet is well removed by RO (Anderson et al, 2010; Mawhinney et al, 2011; Drewes et al, 2013; Rice et al, 2013).

[4] Where an LRV of 1 represents 90% removal; an LRV of 2 represents 99% removal, etc.

Table 2.4 Validated log reduction values based on challenge testing and operational monitoring sensitivity ($LRV_{C\text{-test}}$ and LRV_{OMS}) for indicative treatment processes[a]

Treatment process	$LRV_{C\text{-test}}$ [b]			Basis for validation	LRV_{OMS} [b]			Basis for validation
	Bacteria	Viruses	Protozoa[c]		Bacteria	Viruses	Protozoa[c]	
Secondary wastewater treatment (without disinfection)	3	2.5	2	Reported pathogen removals[1,2]	1	0.5	0.5	Pathogen removals from well operated and designed plants[3] (see Table 3.1 for operational parameters). LRVs can be increased using system specific testing
Soil-aquifer treatment	6	6	6	Reported pathogen removals[4,5,6]		System specific		LRVs dependant on nature of soil and retention time in the aquifer[4,5,6]
Membrane bioreactor	5	5	6	Reported pathogen removals[4,7]	4	1.5	2	5th percentiles of published LRVs using probability density functions correlated with operational characteristics (see Table 3.1 for parameters)[7,8]
Microfiltration or ultrafiltration	6	4–6	6	Challenge testing. Ultrafiltration provides greater removal with the lower LRV for viruses achieved using MF and the higher LRVs using UF[2,9,10]	4	0[d]	4	Daily direct integrity testing supported by online turbidity. Higher LRVs for ultrafiltration[2,9,10]
Ozone-biological activated carbon	6	6	3	Achieving an ozone Ct of ≥30 mg.min/L at ≥10°C[9,11]	4	4	0	Achieving an ozonation Ct of ≥1 mg.min/L at ≥10°C[9,11] Higher Ct values could increase LRVs
Reverse osmosis	6	6	6	Challenge testing[12]	1.5–2 2.5–4	1.5–2 2.5–4	1.5–2 2.5–4	Online monitoring of conductivity or total organic carbon Off-line monitoring of sulfate or online/off-line monitoring of fluorescent dyes[2,5,12]
Ultraviolet light disinfection	6	6	6	Transmitted UV dose of 186 mJ/cm^2 can provide a 4-log inactivation of viruses. At an extrapolated dose of 235 mJ/cm^2 6-log inactivation can be achieved. Lower doses required for protozoa and bacteria[9,13,14,15]	6	6	6	See basis of $LRV_{C\text{-test}}$
Ultraviolet light/advanced oxidation process	6	6	6	Major contribution by UV. Oxidant dose also provides inactivation[3,5]	6	6	6	See basis of $LRV_{C\text{-test}}$
Chlorination	6	6	0	Achieving a Ct of 15 mg.min/L at pH 7.5 and ≥10°C[16]	6	6	0	See basis of $LRV_{C\text{-test}}$
Drinking-water treatment plant (coagulation, flocculation, filtration, chlorination)	6	6	3–4	Default values for protozoa based on meeting turbidity requirements and achieving chlorine Ct values for virus and bacteria reductions (as above)[2,9,16,17]	6	6	3–4	See basis of $LRV_{C\text{-test}}$

Notes:

[a] Generally LRV_{OMS} based on challenge testing and sensitivities of operational monitoring should be used, particularly where operational monitoring is relied upon for demonstrating ongoing performance of treatment processes. However, proponents, in consultation with regulators, can choose whether $LRV_{C\text{-tests}}$, which are based only on challenge testing, can be used.

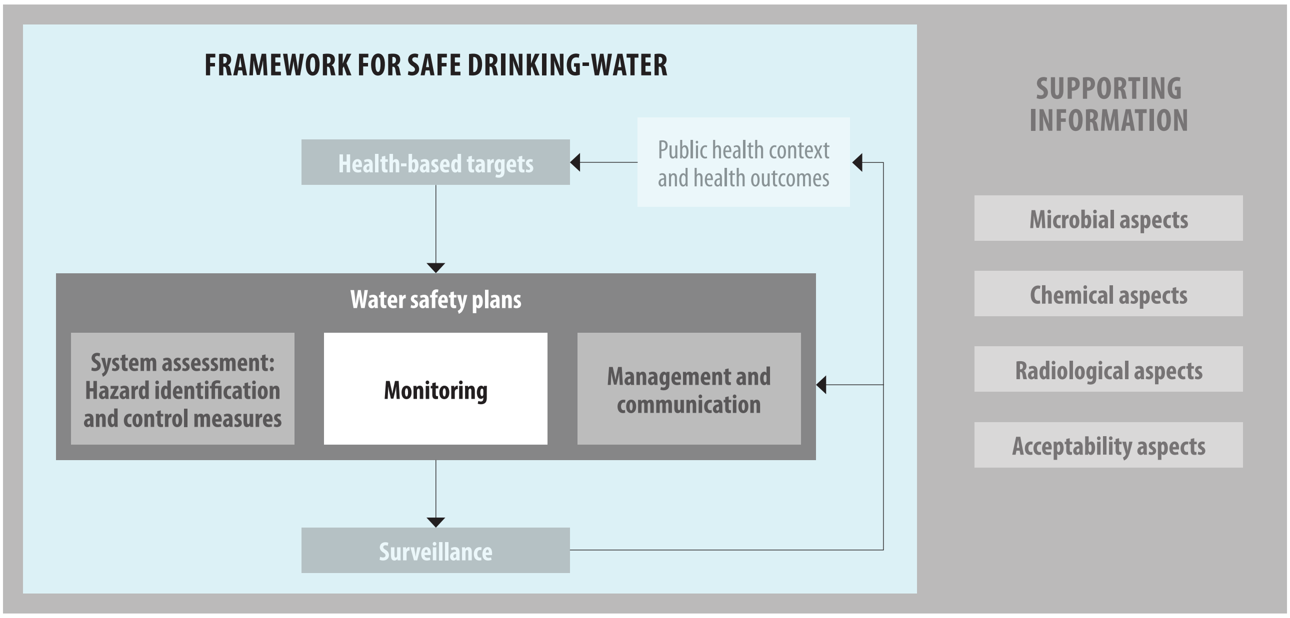
[b] Challenge testing performed in laboratory testing or field trials. Upper LRV of 6 used. In the case of disinfectants this is typically an extrapolation of observed results.

[c] Protozoa LRVs based on *Cryptosporidium*.

[d] LRVs for viruses can be validated on a case-by-case basis.

[1] WHO (2006), [2] TWDB (2015), [3] Department of Health, State of Victoria (2013), [4] Betancourt et al (2014), [5] NRC (2012), [6] Pang (2009), [7] Branch & Le-Clech (2015), [8] Waterval (2016a), [9] WHO (2017a), [10] USEPA (2005), [11] USEPA (1999), [12] Pype et al (2015), [13] USEPA (2006b), [14] Hijnen et al (2006), [15] Tchobanoglous et al (2015), [16] Keegan et al (2012), [17] USEPA (2006a).

3. MONITORING



KEY MESSAGES

1. Operational monitoring of potable reuse schemes should incorporate continuous monitoring linked to supervisory control and data acquisition (SCADA) systems with automatic alarms for deviation from critical limits.
2. Parameters for monitoring operational performance of processes used to achieve pathogen control include physical tests (e.g. turbidity for filtration), chemical tests (e.g. TOC, sulfate or fluorescent dyes for RO) and disinfectant residuals and contact times.
3. Limited sets of indicator chemicals can be used to monitor operation of control measures used for chemical contaminants.
4. Verification will follow the same approach used for other drinking-water supplies.
5. Bioassays may become useful tools in the future for assessing chemical quality of drinking-water but further work is required to understand the public health significance of results. Potential use as part of treatment performance assessment is promising.

3.1 Operational monitoring of control measures

Operational monitoring is at the centre of WSPs and is the planned set of measurements and activities to determine that control measures are operating effectively (i.e. is it working now?). A comprehensive monitoring and control system is necessary to measure and track the performance of treatment processes to ensure that operational targets are being met. Monitoring needs to be undertaken at a frequency that will enable rapid and timely responses if significant deviations occur that could affect water quality. Operational monitoring is particularly important in potable reuse systems because of the need to deal with the potential for substantial source water variabilities and the relatively high levels of microbial and chemical hazards. Operational monitoring should be implemented for all control measures, starting in the wastewater collection system and ending at delivery of drinking-water to consumers. For example, online VOC sensors are used in Singapore (see Case Study 4) to provide early warnings of unauthorized industrial discharges that could threaten the production of safe drinking-water by the NEWater schemes. Other parameters measured in wastewater collection systems could include pH as a signal for changes in discharges and conductivity (electrical conductivity or TDS) as a measure of saline intrusion. Operational monitoring should include regular inspections of controls and treatment applied to discharges from industrial premises and medical facilities.

In comparison to conventional surface or groundwater supplies, the flow and composition of treated wastewater from urban treatment plants can change greatly across the course of a single day and often varies substantially during weekends, holidays or during special events. Monitoring programmes need to measure source water variability to maintain performance of potable reuse treatment trains. Parameters such as ammonia, nitrate, nitrite, TOC, VOCs and turbidity/suspended solids can be used to measure variations in wastewater quality. Ammonia, TOC and turbidity can be measured online while the other parameters can be measured rapidly and frequently using grab samples. Volatile organic compounds can also be measured online but are generally measured less frequently using grab samples.

Tiered operational monitoring programmes that emphasize those methods that produce data quickly are critical so that process anomalies can be detected before finished water is adversely affected. It is strongly recommended that the performance of treatment processes should be monitored using online meters with real-time data reporting wherever possible. Where online monitoring is performed, results should be regularly calibrated using grab samples and bench top analyses. When online monitoring is not practical, frequent grab samples, using rapid analytical procedures, can be alternatives.

3.1.1 Operational monitoring parameters

Having monitoring data available to prevent and correct deterioration of the performance of each unit barrier in a treatment train is the key to assuring consistent production of safe drinking-water. Monitoring of unit processes at control points within a treatment train requires identification of appropriate parameters and target criteria to define operational performance acceptability. Target criteria can take the form of operational limits and critical limits. Critical limits for treatment processes used in potable reuse separate acceptable from unacceptable performance and loss of confidence in water safety. Depending on the nature of the control measure, critical limits can be upper limits (e.g. filtered water turbidity), lower limits (e.g. disinfectant Ct values) or ranges of values (e.g. pH). Operational limits are typically used as early warning signals that performance of control measures is deteriorating, and enable implementation of corrective action before critical limits are breached. Frequent operational monitoring to confirm that individual treatment barriers are operating within design criteria provides assurance that drinking-water quality targets are being achieved.

Consistent with the operation of conventional public water systems, both acute and chronic risks must be managed. The presence of microbial pathogens is by far the greatest concern with respect to potential acute impacts on human health in public water supplies. Changes in operational monitoring parameters that imply a lesser level of microbial removal or inactivation will require immediate corrective responses such as reducing water flow rates or boosting disinfectant doses. Chronic risks, usually from potential chemical concentrations, must also be managed. While deviations in operational parameters for chemical contaminants should be corrected as rapidly as feasible, risks are usually associated with long-term exposures and usually would not require implementation of emergency measures.

Operational monitoring of pathogen control measures

In potable reuse, pathogen control is achieved by a combination of physical removal and inactivation processes. The most widely used operational monitoring parameters are disinfectant residuals and physical removal parameters such as turbidity, monitored online. Table 3.1 provides a summary of operational monitoring parameters and testing frequencies for a range of indicative treatment processes commonly used in potable reuse schemes for pathogen removal. Microbial parameters, such as *E. coli*, coliphages, *Clostridium perfringens*, aerobic spores and enterococcus, are currently not suitable operational parameters largely because of the time required for analysis. This may change in the future as progress is being made on the development of rapid tests for microbial indicators, such as coliphages, which could be particularly useful for monitoring physical removal of viruses. Similarly, next generation sequencing may provide a basis for future monitoring.

Physical and chemical tests: Integrity of low-pressure membranes (MF and UF) can be assessed by online turbidity measurements and periodic (daily) pressure decay tests (USEPA, 2005). Turbidity measurements can be made online and rapidly by grab sampling. Integrity of high pressure membranes (such as RO or NF) can be monitored by online measurement of electrical conductivity (representing TDS rejection) and TOC.

Table 3.1 Examples of operational monitoring parameters for indicative treatment processes used to provide pathogen removal

Treatment process	Operational monitoring parameters	Frequency	Notes
Secondary treatment	Ammonia, nitrate/nitrite, biochemical oxygen demand, suspended solids, dissolved oxygen, mixed liquor suspended solids, hydraulic retention time, solids retention time, flow	Online for dissolved oxygen, ammonia, flow Weekly for other parameters	Achieves LRVs but no quantitative correlation with individual operational parameters Default LRVs based on achieving good operating characteristics
Soil-aquifer treatment (surface spreading, percolation retention)	Flow Total organic carbon Total nitrogen, nitrate, nitrite	Online Weekly Quarterly	Total nitrogen, nitrate and nitrite measured in water from observation bores
Membrane bioreactor	pH, bioreactor dissolved oxygen, solids retention time, hydraulic retention time, mixed liquor suspended solids, transmembrane pressure flux, turbidity	Online for parameters such as pH, turbidity, dissolved oxygen, transmembrane pressure Weekly for other parameters	Achieves LRVs but no quantitative correlation with individual operational parameters Default LRVs based on achieving good operating characteristics
Microfiltration or ultrafiltration	Turbidity Pressure decay test	Online Daily	Can achieve <0.1 NTU
Media filtration	Turbidity	Online	Can achieve <0.15 NTU Monitoring of individual filters improves control
Ozone-biological activated carbon	Ozone Ct Temperature	Online	LRVs based on ozone Ct
Reverse osmosis	TOC or conductivity Sulfate or fluorescent dyes	Online Daily	Lower LRVs based on TOC or conductivity Higher LRVs if daily off-line measurements of sulfate or fluorescent dyes used, as well as TOC or conductivity
Ultraviolet light disinfection	UV intensity UV transmission Flow	Online	LRV based on UV dose Monitoring used to determine UV dose received by waterborne microorganisms
Ultraviolet/advanced oxidation process	UV intensity UV transmission Flow	Online	LRVs based on UV dose. Oxidant dose also contributes to LRVs Monitoring used to determine UV dose received by waterborne microorganisms
Chlorination	Chlorine Ct pH Temperature	Online or frequent grab samples	LRVs for bacteria and viruses based on chlorine Ct
Drinking-water treatment plant Coagulation, flocculation, filtration Chlorination	Turbidity Chlorine Ct	Online Online or frequent grab samples	LRVs dependent on target turbidity criteria (0.15–0.3 NTU) and whether individual filters monitored

Disinfectant residuals: Disinfection processes should be designed to achieve specified disinfectant concentrations for set periods of time (Ct in mg.min/L where C = concentration of the disinfectant in mg/L and t = time in minutes) to provide designated log reductions of pathogens. Online and grab samples for disinfectant residuals provide almost instantaneous performance information regarding in situ disinfectant concentration. The monitoring output allows for rapid adjustment of disinfection doses, when needed. Other parameters such as pH and turbidity are also important components that should be regularly monitored for ensuring effective disinfection. Ultraviolet lamp performance can be monitored by percentage transmission and UV intensity.

Operational monitoring of chemical control measures

Prevention of source water contamination is a key component of assuring safety (USEPA, 2011; WSAA, 2012; Mosher et al, 2016). Discharges from industries and medical facilities should be regulated and subject to controls, ongoing inspections and audits. This should be supported by monitoring of wastewater quality at key points in collection systems using online monitoring of parameters such as pH, conductivity and VOCs.

For chemical contaminants, attenuation generally occurs through biological transformation, adsorption, physical removal or chemical oxidation. Thus, appropriate surrogate parameters are needed for each general type of process. Source waters for potable reuse can potentially contain a wide range of chemical contaminants and a nearly infinite number of transformation products (Section 2.2) but risks associated with exposures to trace chemicals are usually of longer term and even lifetime exposure concern. Frequent monitoring for every potential chemical substance is not practical, plausible or necessary. A sound selection framework is needed that can provide a list of meaningful indicator measurements that can represent key groups of contaminants, taking into account human health significance and assurance of proper performance of water treatment processes (Drewes et al, 2008; 2013). The surrogate and indicator approach allows for relatively rapid and comprehensive monitoring without frequent measurement of large numbers of chemicals (Drewes et al, 2008; 2013; Crook et al, 2013; TWDB, 2015). Surrogate parameters suitable to measure performance of unit processes are bulk parameters that often can be monitored using online monitoring or high-frequency grab samples and can be used for real-time decision-making for process control. Examples include total TOC, VOC and conductivity (Table 3.2).

Chemical indicators will most often be measured using laboratory-based testing that may require several days to complete. Fairly frequent measurements should be made of the selected indicator chemicals. More comprehensive but less frequent monitoring of chemicals will typically be included in verification monitoring (Section 3.2). Chemical indicators are specific substances that are likely to be detectable in raw water and are representative of larger classes of chemicals. Ideally, indicators that are normally relatively well attenuated and relatively persistent are selected to provide a meaningful assessment of performance (Drewes et al, 2008). For example, boron is normally present in reasonable concentrations in wastewater and is partly removed by RO. Monitoring for boron can provide an assessment of RO performance in removing low molecular weight chemicals (Drewes et al, 2008).

Table 3.2 Examples of surrogate parameters for chemical removal by indicative control measures

Control measure	Surrogate parameter	Monitoring frequency	Notes
Source water control	VOCs, pH, conductivity (conductivity/ total dissolved solids)	Online	Rapid changes should be investigated to determine source
Reverse osmosis **Nanofiltration**	TOC, conductivity/TDS	Online	Provides an indication of performance in bulk removal of chemicals
	Dissolved organic matter by excitation-emission matrix fluorescence	Online	
	VOCs	Daily/weekly	
Activated carbon	Fluorescence and UV absorbance	Online	Trace organic chemical removal
Ultraviolet/advanced oxidization process	Fluorescence and UV absorbance	Online	Trace organic chemical removal

Source: Adapted from: Singh et al (2012), Anumol et al (2015), Merel et al (2015a), Yu et al (2015).

Examples of chemical indicators that could be selectively applied for periodic performance monitoring of two potable reuse treatment trains is provided in Table 3.3. It should be noted that the concentrations in wastewater, even after secondary treatment, are well below estimated health criteria values. Table 3.3 includes the chlorinated sweetener sucralose which is one of the most widely applied indicator species in the USA (Mawhinney et al, 2011; Rice et al, 2013). However, the use of sucralose is not as prevalent in all countries and it may not be a suitable indicator in large portions of the world. Caffeine has also been suggested as a candidate indicator, but it is biodegradable and therefore less reliable as a performance indicator.

Table 3.3 Examples of indicator chemicals that can be used to monitor performance of two treatment trains

	Concentrations (ng per L)								
				Treatment train 1			Treatment train 2		
Constituent	Estimated health criteria[a]	Method reporting limit	After secondary treatment	After ozonation	After biological activated carbon	After ultraviolet photolysis	Micro-filtration filtrate	Reverse osmosis permeate	After ultraviolet/ hydrogen peroxide
Atenolol	4000	3	292	<MRL[b]	<MRL	<MRL	NT[c]	<MRL	<MRL
Carbamezapine	10 000	1	194	<MRL	25	21	NT	<MRL	<MRL
N,N-Diethyl-3-methylbenzamide (DEET)	200 000	6	45	<MRL	<MRL	<MRL	NT	<MRL	<MRL
Estrone	320	31	<MRL	<MRL	<MRL	<MRL	NT	<MRL	<MRL
Meprobamate	200 000	3	380	158	178	170	NT	<MRL	<MRL
Primidone	10 000	7	4100	525	323	186	NT	7	75
Sucralose	150×10^6	77	24 800	17 200	19 700	21 700	NT	<MRL	<MRL
Tris(2-chloroethyl) phosphate	5000	77	<MRL	<MRL	<MRL	<MRL	NT	<MRL	<MRL
Triclosan	2 100 000	8	128	<MRL	<MRL	9	NT	<MRL	<MRL

[a] Health criteria were estimated by Crook et al (2013) from existing toxicological data; [b] MRL = method reporting limit; [c] NT = not tested.
Source: Tchobanoglous et al (2015). With permission from the WateReuse Research Foundation (Water Environment & Reuse Foundation report number Reuse-14-20).

A practical example of the use of a limited set of chemical parameters is provided in the case study for the Perth, Australia potable reuse scheme (see Box 3.1 and Table CS5.3). In this case, a suite of 15 chemicals representing DBPs, inorganic and organic chemicals, pharmaceuticals, hormones, pesticides and phenols are used to assess treatment performance. These parameters are monitored at a higher frequency than those included in verification monitoring.

For regulated chemicals, standardized methods are generally available and should be followed. However, for indicator chemicals this is not always the case and method reporting limits can vary by orders of magnitude among laboratories (Vanderford et al, 2012; Drewes et al, 2013). Many chemical indicator species will occur in ng per L concentrations in treated wastewater and often are non-detectable in finished waters. In addition, usage may vary substantially depending upon geographical region (e.g. sucralose) and industrial input into the sewer system. Indicators should be selected that are relevant to local conditions and that preferably have standardized methods with suitable detection limits (Vanderford et al, 2014). It is also extremely important to use a high degree of quality control for indicator monitoring, since many of the selected substances are ubiquitous in the environment. For example, substances like caffeine and some flame retardants are common and laboratory contamination of samples and blanks can be an issue when attempting to measure ng per L concentrations. Thus a strong quality assurance programme with replicate samples, laboratory and field blanks, and matrix spikes is crucial for trace indicator analyses.

Box 3.1 Indicator chemicals used for the Beenyup potable reuse scheme, Perth, Australia

The parameters measure performance of the advanced WWTP and were agreed in a memorandum of understanding between the operator of the scheme (the Western Australian Water Corporation) and the State Department of Health (see Case Study 5).

Indicator parameters	Guideline value	Unit	Chemical group represented
Boron	4	mg/L	Inorganic chemicals
N-Nitrosodimethylamine	100	ng/L	Nitrosamines
Nitrate as nitrogen	11	mg/L	Inorganic chemicals
Chlorate	0.7	mg/L	Inorganic DBPs
1,4-Dioxane	50	µg/L	Organic chemicals
Chloroform	200	µg/L	Other DBPs
Fluorene	140	µg/L	Organic chemicals
1,4-Dichlorobenzene	40	µg/L	Organic chemicals
2,4,6-Trichlorophenol	20	µg/L	Phenols
Carbamazepine	100	µg/L	Pharmaceuticals and personal care products
Estrone	30	ng/L	Hormones
Ethylenediaminetetraacetic acid	250	µg/L	Organic chemicals
Trifluralin	50 000	ng/L	Pesticides and herbicides
Diclofenac	1.8	µg/L	Pharmaceuticals and personal care products
Octadioxin	9000	pg/L	Organic chemicals

3.1.2 Long-term assessment of operational monitoring

Operational monitoring is used for timely and typically short-term assessment of the performance of control measures. It is also important to regularly examine accumulated operational monitoring results to check for trends that might indicate changes in performance. Trends may be manifested in increasing frequencies of non-compliance with critical and operational limits but can also be manifested in the absence of non-compliances. The basis for any deterioration in performance over time should be investigated and corrected.

3.2 Verification

Verification provides a final check on the suitability of produced drinking-water quality for the health protection of consumers. Verification provides an assessment of the effectiveness of WSPs in achieving compliance with health-based targets. Verification of water quality will typically include testing for faecal indicator organisms and hazardous chemicals with regulatory limits. Verification should include testing of water produced by each treatment plant, where potable reuse systems can include separate wastewater and drinking-water treatments plants, and of drinking-water as supplied to consumers. As discussed in the previous section, quality assurance and quality control programmes are essential, including the use of standardized methods and certified/accredited laboratories wherever possible. This is vital to ensure confidence in results and to enable proper interpretation of results.

Sampling frequency should consider potential variability in results, outcomes, and costs and benefits (WHO, 2017a). All testing needs to have a defined purpose with responses established to deal with all types of results. Since microbial contaminants pose the greatest risk to public health from acute exposure, monitoring is generally more frequent. Conversely, since chemical risks are usually associated with chronic exposure with limited exceptions (e.g. copper and nitrate) monitoring will typically be conducted less frequently.

3.2.1 Microbiological water quality

Monitoring for microbial pathogens in drinking-water is impractical and of little value (Section 5.1). The traditional approach to verifying microbial quality of drinking-water is the use of faecal indicators such as *E. coli* or, alternatively, thermotolerant coliforms. Drinking-water should contain no *E. coli* per 100 ml (WHO, 2017a). In conjunction with evidence from operational monitoring that microbial performance targets are being met on an ongoing basis (Section 3.1), the absence of *E. coli* which is present in high numbers in wastewater, provides assurance of microbial safety.

In addition to testing for *E. coli*, measurement of disinfectant residuals within distribution systems is a useful, rapid and low cost method that can be used to provide an indicator of microbiological quality, particularly for bacteria and viruses. These measurements serve a different purpose than operational monitoring of disinfectant residuals at the outlets of treatment plants to ensure that required Ct values or doses (for UV light) have been achieved.

A limitation of *E. coli* is that it is not a particularly good indicator of enteric viruses and protozoa which are more resistant to environmental pressures. Use of other indicators, including coliphages (for viruses), *Clostridium* spp. (for protozoa) and enterococci, have been suggested and could be considered for inclusion in verification monitoring but they also have limitations. Coliphages share some properties with enteric viruses and can be present in high numbers in wastewater (Table 2.2) but there is no direct correlation between numbers of coliphages and enteric viruses in drinking-water (WHO, 2017a). *Clostridium* spores are far more resistant to environmental pressures and disinfection than protozoa and as a result are conservative indicator organisms that can be present long after contamination events. Detection of *Clostridium* spores in drinking-water needs to be treated with caution (WHO, 2017a).

Guidance on locations and frequency of monitoring is provided in the GDWQ.

3.2.2 Chemical water quality

Monitoring programmes for chemical quality need to consider a number of factors, including:

- source water quality and variability (Thompson et al, 2007). In the case of IPR schemes, this should include consideration of the environmental buffer;
- inputs that can influence source water quality (e.g. industrial discharges);
- the type of treatment processes and treatment chemicals used. For example, the range of DBPs included in testing will depend on the type of disinfection;
- availability of certified analytical facilities; and
- regulatory requirements.

Beyond chemicals with regulatory limits or guideline values, potable reuse system operators may seek to better characterize the potential occurrence of industrial chemicals, emerging contaminants and yet unknown chemical constituents (Snyder, 2014). There are ever increasing numbers of chemicals that have been identified in wastewaters at diminishingly minute levels. Care should be taken to only include chemicals that are of potential concern based on chemical hazard identification for the potable reuse system (Thompson, et al 2007) (see Chapter 2).

Monitoring locations and frequency of testing will depend on the source of the chemical, variability in concentrations and the likelihood of changes occurring within distribution systems. Most chemicals can be tested in water entering distribution systems. For substances that may change within the distribution system, for instance DBPs and metals released by corrosion, monitoring may be required in both the finished water and multiple points within the distribution system. Substances that do not vary in concentration substantially over time require less frequent monitoring than those that might, such as industrial chemicals.

Testing for "emerging contaminants" may increase confidence by operators and consumers in the safety of drinking-water supplies. This is more likely to be required during initial start-up and commissioning periods. If such testing is to be undertaken, it is important that mechanisms are established to interpret and if necessary to respond to results. Setting of screening values is discussed in Section 5.2.2. Alternatives for testing for individual emerging contaminants include non-targeted analyses to detect the potential presence of individual contaminants and biological assays to detect the activity and removal of complex mixtures (see Boxes 3.2 and 3.3).

3.3 Monitoring during start-up of new treatment facilities

Starting the operation of a complex water treatment plant involves a number of activities, including individual and combined process testing, commissioning and acceptance, and initial operator training. Water quality monitoring and the development of baseline performance data are also integral activities in demonstrating the operational performance of any new facility (Tchobanoglous et al, 2015). This should include operational monitoring of treatment processes and verification testing for chemical parameters and faecal indicator bacteria. For potable reuse, it would be prudent to increase monitoring frequencies during start-up and commissioning to provide confidence in the effectiveness of individual processes and the treatment train as a whole. Disinfection by-product formation potential should also be determined.

Once a plant has been commissioned, it is common for it to then enter a proving period in which the plant is operated continuously to demonstrate functionality. A period of 30 days is often used although longer periods can be applied. Water quality monitoring data obtained during this period should be designed to document and verify that all components of the treatment train meet specifications and are protective of public health. The data will also serve as a baseline of system performance for future comparisons and analysis.

Box 3.2 Non-targeted chemical analyses

One mechanism to comprehensively evaluate the occurrence and attenuation of chemicals in potable reuse systems is to conduct non-targeted analysis to better elucidate tentatively identified compounds. These compounds are not necessarily candidates for future GDWQ development or regulations. Their immediate value is as site-specific indicators of source water content and treatment technology performance. Today, the most common tool for non-targeted analysis is mass spectrometry, which can tentatively identify chemicals compared with a library of compounds with established characteristics (mass to charge ratios). The method includes extraction and concentration of chemicals from water samples; separation processes using either gas chromatography for volatile chemicals or liquid chromatography for lower volatility species; and ionization. These types of analytical instruments are relatively expensive and technically complicated to operate. In addition, they cannot detect all potential substances. However, non-targeted analyses can provide a higher degree of specificity in identifying individual chemicals that are capable of breaching a particular treatment barrier.

Box 3.3 Potential use of bioanalytical tools

Assessing the presence and possible risks associated with drinking-water can be a challenge because of the usually low concentrations of individual chemicals and complex mixtures that may occur. Bioanalytical tools offer a path toward more comprehensive chemical evaluations of water – by detecting chemicals not by their structure but by their biological activity. This provides an improved capacity to detect categories of non-target compounds at low concentrations and some measure of mixture interactions at low doses.

Bioanalytical tools are molecular or cell-based in vitro bioassays adapted to testing of water and/or concentrated water extracts (e.g. solid phase extracts). They have grown in complexity from bioassays for mutagenicity (Ames test) and genotoxicity (umuC bioassay) to encompass an ever growing range of biological end-points (NRC, 1998; Leusch & Snyder, 2015).

It is difficult to simplify the vast diversity of available bioassays, which incorporate various and often overlapping modes of action, and at the same time remain scientifically accurate. One compromise suggested by Escher and Leusch (2012) is to sort bioassays into five broad categories based on a simplified cellular toxicity pathway: one group is a measure of metabolic response, three are based on the type of interaction with the target molecule (non-specific, specific and reactive toxicity), and the fifth is a measure of cellular defence mechanisms (adaptive stress response).

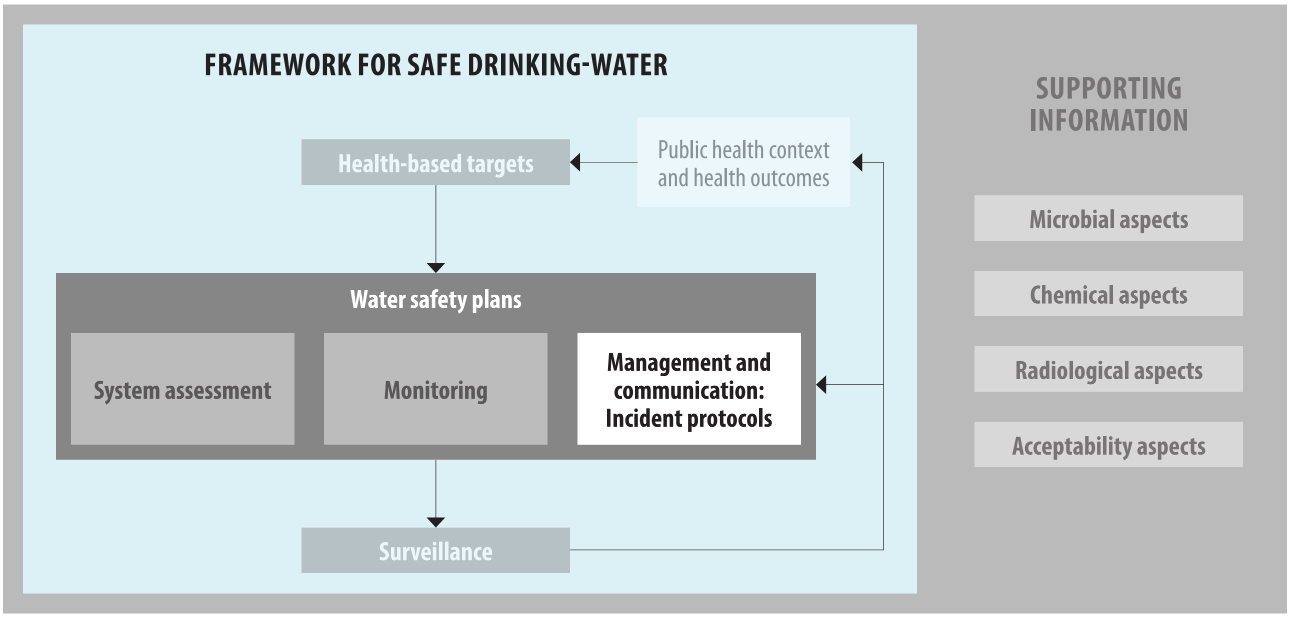
There is still significant uncertainty regarding the potential role of bioanalytical tools in a regulatory context. In vitro bioassays measure the initial interaction of the xenobiotic at the molecular or cellular site, and generally do not take into account toxicokinetic modulators of toxicity (absorption, distribution, metabolism and excretion). In addition, defence and repair mechanisms can compensate for toxic injury in whole organisms. Therefore, it is difficult to relate in vitro responses to adverse human health effects.

The Australian Guidelines for Water Recycling (NRMMC-EPHC-NHMRC, 2008) recognize the limitation of current chemical methods to deal with complex mixtures and indicate that in vitro bioassay screening could be used as a screening and prioritization tool for subsequent chemical analysis.

A recent study applied 103 bioassays for approximately 30 end-points to various water samples, including treated wastewater. The study reported a significant response with treated wastewater in most end-points, but a gradual loss of activity in most assays during advanced treatment, with only a few assays detecting activity in the treated wastewater (Escher et al, 2014). This finding agrees with other studies that have monitored these end-points in recycled water (Leusch & Snyder, 2015). The potential use of a small group of bioassays as part of treatment process evaluation and selection is a particularly promising area.

Further work is continuing on bioanalytical tools and if successful, it should provide greater public confidence in the capability of potable reuse schemes to produce safe drinking-water. Developments in bioanalytical science should be monitored to identify useful candidate assays as they are validated.

4. MANAGEMENT AND COMMUNICATION: INCIDENT PROTOCOLS



KEY MESSAGES

1. **While the aim is to maintain compliance with water quality requirements at all times, considered and controlled responses to non-compliance are essential for protecting public health and maintaining public confidence.**
2. **Incident protocols should be developed in consultation with regulatory agencies and identify responsibilities and authorities of stakeholders, incident criteria, reporting requirements, internal and external communication protocols and emergency contact lists.**
3. **Mechanisms for issuing public advisories (boil water or avoidance advisories) should be developed before they are needed.**
4. **WSPs and protocols should be reviewed following significant incidents.**

Management plans describing actions to be taken in response to incidents and emergencies are an important component of WSPs for all drinking-water supplies (WHO, 2017a). While the aim should always be to operate drinking-water schemes to continuously produce safe drinking-water, incidents will occur and response protocols need to be prepared to deal with them. Considered and controlled responses to incidents that may compromise water safety are essential for protecting public health and maintaining consumer confidence. In many cases the key to maintaining safety will be implementation of rapid and effective responses. Responses to incidents need to be planned, coordinated and executed in an orderly and timely fashion. In the event of significant incidents or emergencies, maintaining consumer trust is essential. This will be influenced by how incidents and emergencies are handled and communicated. All agencies involved in responses need to be fully informed, aware of their responsibilities and act in a coordinated manner.

4.1 Organizational understanding

Potable reuse schemes are complex systems that need to be managed and operated by well trained and skilled staff. Managers and operators need to understand what is expected as part of normal operation and the systems that are in place to detect deviations from normal operations such as SCADA and automatic alarm systems. Managers and operators should contribute to development of incident response and communication criteria and understand the significance of non-compliance.

SCADA systems and automatic alarms must be monitored 24 hours a day, seven days a week, to enable implementation of rapid responses. Operators should be trained to always respond to alarms and to never change settings or turn off alarms without receiving direction from an appropriate supervisor/manager. Alarm systems should be programmed to stop supply if critical limits are not met. Supply should only be resumed when normal operation can be assured.

Incident and emergency response protocols should be regularly tested to ensure that they are effective and understood. This can involve running mock scenarios.

4.2 Structure of incident protocols

Incident and emergency response protocols should be developed and documented prior to potable reuse schemes being commissioned. Protocols need to operate 24 hours a day, seven days a week. Two types of protocols should be developed: external protocols supporting coordinated interagency responses to significant public health incidents; and internal protocols within drinking-water suppliers to deal with lesser incidents that if dealt with appropriately will prevent incidents developing to a level requiring public notification. Significant incidents should be notified verbally (i.e. telephone). Notification by electronic means, while often effective, cannot be guaranteed to always be read promptly by intended recipients.

External protocols should be developed in consultation with regulatory agencies.

Incident protocols for potable reuse schemes should be based on the same principles as protocols for any other type of drinking-water system (WHO, 2017a). Points of variation could include consideration of specific characteristics of wastewater and wastewater collection systems, trade waste controls, types of treatment processes, possible use of environmental buffers or engineered storages and blending. Key issues to be considered when designing protocols are shown in Box 4.1.

Box 4.1 Indicative content of incident protocols

1. Incident criteria such as:
    - non-conformance with health-based targets;
    - non-conformance with critical limits (e.g. exceedance of filtered water turbidity, failure to meet UV intensity required for advanced oxidation, failure to meet disinfectant Ct values);
    - accidents/spills that increase levels of contaminants (e.g. discharge of industrial waste into sewerage systems);
    - treatment failure;
    - prolonged power outage; and
    - extreme weather (e.g. floods, cyclones) and natural disasters (e.g. fires, earthquakes).
2. Requirements to report unforeseen and undefined incidents that could represent significant risks.
3. Reporting requirements including timelines and methods (e.g. significant incidents notified verbally within one hour).
4. Responsibilities of all stakeholders.
5. Communication protocols and strategies including notification procedures (internal, regulatory authorities, key agencies, senior management, consumers and media).
6. Communication protocols between wastewater and drinking-water treatment plant operators, particularly when managed by separate entities.
7. Emergency contact lists.

Incident criteria should include considerations of magnitude and duration. For example, short-term spikes (e.g. under 15 minutes) in filtered water turbidity, while not ideal, do not necessarily represent a treatment failure; similarly, loss of disinfection for a short period of time may not lead to unsafe water being released if there is a large treated water storage between the disinfection plant and consumers. Time limits should be based on knowledge of the water system.

Clusters of customer complaints should be considered as an incident. Complaints such as off-tastes and odours, unusual colour, increased turbidity, reduced water pressure and illness, could signal contamination events and should be investigated. It may be useful to establish different categories of incidents, including:

- Minor incidents that can represent small risks to health but represent early warning signals (e.g. temporary non-compliance with critical limits, minor exceedance of health-based targets).
- Major incidents that if not managed can potentially represent a significant risk to public health.
- Priority incidents and emergencies that if not managed represent a high likelihood of a significant risk to public health.

As a general rule, major or significant incidents are more likely to be associated with failures that threaten microbial safety. Exposure to microbial pathogens can produce acute impacts and these incidents will typically require rapid responses. Short-term exceedances of chemical quality will generally be minor in nature and require responses such as additional sampling to confirm exceedances and investigate causes. Most chemicals only cause public health impacts following long-term exposure to elevated concentrations. Guidance on how to respond to exceedance of parameter limits can be found in Section 8.7 of the GDWQ (WHO, 2017a).

While it is important that incident protocols are comprehensive and define all incidents that may have public health impacts, it is also important that protocols should not be excessively detailed. Incident protocols should not be used simply to reinforce good management practices; this is the role of normal documented WSP procedures and training of personnel. The inclusion of too many incidents, particularly too many incidents that do not warrant immediate responses, can lead to incident fatigue and the danger that significant incidents will be overlooked and not receive appropriate attention.

Given the complexity of potable reuse schemes, one approach could be to divide the protocol into sections dealing with separate components of the drinking-water supply (wastewater system, environmental buffers, treatment processes, blending water, distribution systems, etc.). In this case, it is essential that communication is maintained between personnel responsible for each component irrespective of whether these personnel are employed within a single agency or multiple entities.

Internal drinking-water supplier or wastewater management protocols should be accompanied by supporting documents describing pre-planned remedial actions, strategies for increased monitoring, sources of alternative and emergency supplies, lists of critical customers (e.g. hospitals, health-care facilities, food manufacturers, etc.) and procedures for discharge of contaminated water.

4.3 Major incidents and emergencies

Protocols should include mechanisms for issuing boil water or water avoidance advisories when emergencies lead to drinking-water being potentially unsafe. These advisories represent responses of last resort and should only be issued when an unacceptable and ongoing risk to public health is identified. They should only be issued after consultation with the relevant public health agency. Boil water advisories are issued when substantial contamination by microbial pathogens is known or suspected. Water avoidance advisories may be required in response to substantial chemical contamination. In the absence of spills, avoidance advisories are unlikely to be required. Further information on boil water and water avoidance advisories is provided in Chapters 7 and 8 of the GDWQ (WHO, 2017a).

4.4 Communication

Effective communication is essential in managing incidents, ensuring coordinated responses and maintaining consumer confidence and trust. There are three immediate questions that need to be considered in responding to incidents and where necessary, in communicating outcomes to consumers:

- What happened? Clear transparent explanations are required.
- When did it happen? Unreasonable delays between occurrence and reporting of incidents will lead to extended exposure of consumers to potentially unsafe water. In addition, delays will indicate a lack of decisive action and erode public confidence.
- What is being done to fix the problem?

A public and media communication strategy should be established before incidents occur. This should include communication, where necessary, to the general public and critical customers (hospitals, health-care facilities, food manufacturers, etc.). Draft communications that are understandable to all consumers, taking into account cultural, educational and language diversity, should be prepared for predictable incidents. Delivery mechanisms, allowing for access and use by consumers, should also be identified. While social platforms are increasing in popularity not everyone uses them, similarly not everyone uses the internet on a regular basis, and television and radio reception may be limited in some areas.

Interagency protocols should identify communication responsibilities of each agency. This should include which agency makes the decision about public notification of incidents and leads communication. In many cases there may be joint responsibilities, for example, the health agency will take the lead on public health matters while the drinking-water supplier will take the lead on operational responses, including repairs and delivery of alternative sources of water, particularly to critical customers. These responsibilities need to be clearly described and understood. It is essential that communications, particularly those released publicly, are consistent and reflect agreed positions. Inconsistent messages will cause confusion and undermine public confidence.

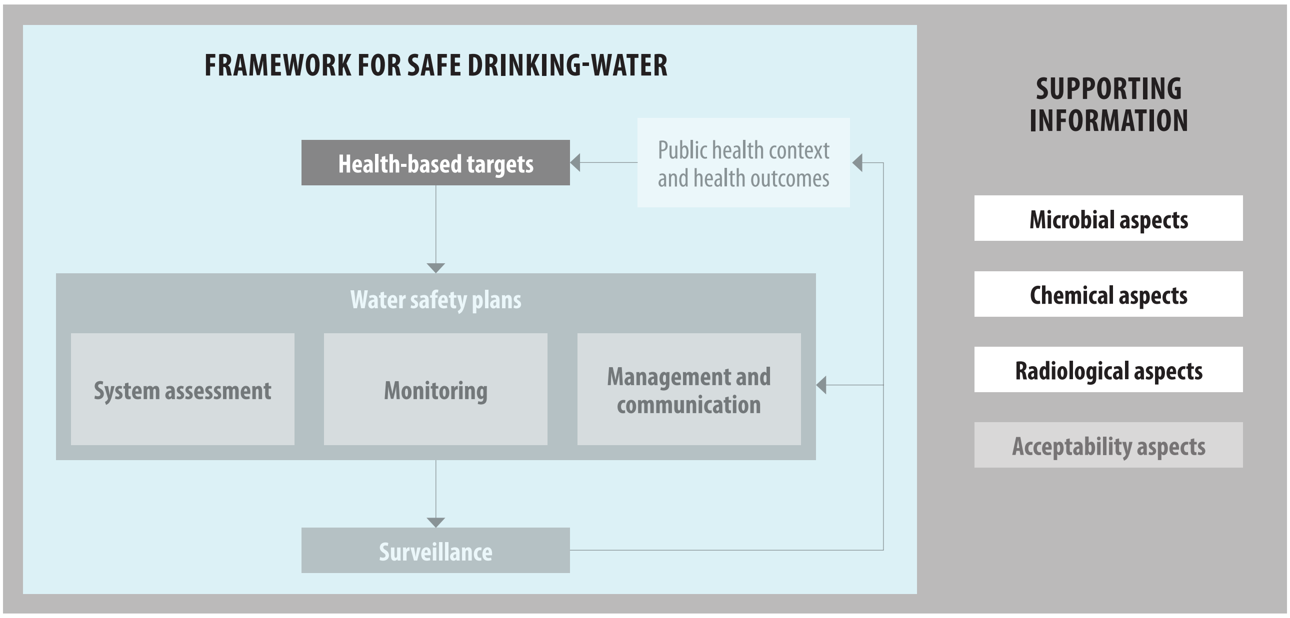
An authoritative and trained spokesperson should be designated to lead communications in the event of an incident or emergency. All employees should be kept informed as they can provide broad informal sources of information. In the case of significant incidents dedicated telephone numbers, email addresses and websites may be needed to provide central sources of information. Contact personnel should be briefed on dealing with inquiries.

4.5 Routine and post-incident reviews

Incident protocols should be reviewed on a regular basis to ensure that they are operating as intended (e.g. annually). Incident reports should be assessed to determine whether certain types of incident are recurring and provide evidence of poor reliability. If such evidence is detected the WSP should be reviewed. The content of protocols should also be reviewed to ensure that they remain current and take into account changes to WSPs and SSPs, including changes to treatment processes, operational monitoring, critical limits, verification and water quality standards. Reviews should include updates of contact personnel.

One of the aims of WSPs is to ensure safety of drinking-water supplies and to minimize occurrence and impacts of hazardous events and incidents. WSPs and protocols should be reviewed and amended if necessary following significant incidents, particularly those involving public notification. The review should include an investigation of the incident and the response. Further information is provided in the Water Safety Plan Manual (Bartram et al, 2009).

5. HEALTH-BASED TARGETS



KEY MESSAGES

1. **Water quality targets (chemical guideline values) and microbial performance targets (log reductions of pathogens in sources waters) are the primary health-based targets for potable reuse. These targets will be underpinned by health outcome targets set by public health authorities or drinking-water regulators (e.g. 10^{-6} disability-adjusted life years (DALYs) per person per year (pppy).**
2. **Microbial performance targets can be identified by using system specific pathogen data in source waters or by using default pathogen concentrations.**
3. **Default performance targets identified in this guidance are 8.5-log reduction of enteric bacteria, 9.5-log reduction of enteric viruses and 8.5-log reduction of enteric protozoa. They do not represent guideline values and are not intended to encourage pathogen monitoring in drinking-water, which would be impractical and of little value for routine monitoring. These values have implications in identifying combinations of treatment processes and operational monitoring requirements, to ensure that the LRVs are being achieved.**
4. **While there tends to be considerable interest in CECs, such as pharmaceuticals and personal care products, the concentrations in drinking-water are generally low and generally do not warrant setting of new guideline values in the GDWQ or national or regional standards.**
5. **In specific circumstances, where a chemical with no guideline value is identified as a concern, approaches for developing screening values are identified to support investigations into potential risks and the need for implementation of additional control measures.**

Health-based targets are risk-based measurable objectives used in the GDWQ (WHO, 2017a) to define the safety of drinking-water. They apply irrespective of the source of drinking-water and apply equally well to potable reuse. Health-based targets provide the basis for assessing risk associated from microbial, chemical and radiological hazards potentially present in wastewater and incorporate four basic forms (see Box 5.1):

- water quality targets
- performance targets
- specified technology targets
- health outcome targets.

Health-based targets, with the possible exception of system specific performance targets, should be set by national or regional health authorities in consultation with stakeholders, including drinking-water suppliers, and should consider economic, social and technical feasibility. The most common form of targets used to define the safety of potable reuse schemes are performance targets (microbial) and water quality targets (chemical guideline values). As with all forms of drinking-water supply, microbial contamination represents the most likely and important risk to public health. Performance targets for potable reuse will typically be much higher than those for other sources of drinking-water due to the relatively high concentrations of pathogens in wastewater. Meeting identified performance targets is of paramount importance.

Box 5.1 Health-based targets and disability-adjusted life years

Water quality targets typically take the form of chemical guideline values and are used as a basis for setting national or regional drinking-water regulations and standards.

Performance targets are typically applied to microbial hazards and represent the minimum reductions in source water pathogen concentrations (measured as log removals) required to meet a health outcome target (see below). Performance targets are usually calculated by water suppliers using methods provided by the health authority or drinking-water regulator. Alternatively, they can be set by the health authority or drinking-water regulator based on default source water pathogen concentrations.[1]

Specified technology targets represent recommended combinations of treatment processes that can achieve safety based on assessments of source water quality. Specified technology targets are typically established for lower resource systems and therefore are not usually applicable to potable reuse schemes.

Derivations of these targets are underpinned by **health outcome targets** determined by health authorities or drinking-water regulators. Health outcome targets define safety in terms of burdens of disease, such as frequencies of diarrhoeal disease or projected increased cancer risks. Health outcome targets in the GDWQ include an upper reference level of risk of 10^{-6} DALYs pppy for microbial pathogens, no or lowest-observed-adverse-effect levels (NOAEL or LOAEL), benchmark dose (BMD) or the lower confidence limit on the benchmark dose (BMDL) for threshold chemicals (e.g. fluoride and copper), and an upper limit cancer risk of 1 excess case per 100 000 people from lifetime exposure to chemical carcinogens (e.g. bromate and NDMA). These targets can be varied depending on local environmental, social, cultural, economic and political circumstances.

DALYs are used to weight health impacts in terms of severity and duration of disease and the number of people affected. In drinking-water they are primarily used for microbial hazards, with 10^{-6} DALYs pppy being approximately equivalent to 1 case of diarrhoea per 1000 people per year. 10^{-6} DALYs pppy is also approximately equivalent to a cancer risk of 1 excess case per 100 000 people from lifetime exposure. The use of DALYs was first included in the third edition of the GDWQ and was retained in the fourth edition as well as the fourth edition incorporating the first addendum.

[1] Examples of default performance targets for potable reuse are provided in the Australian Guidelines for Water Recycling (NRMMC-EPHC-NHMRC, 2008) and by the State of California (Olivieri et al, 2016) (see Appendix 1).

5.1 Microbial performance targets

Microbial performance targets are typically expressed as LRVs of pathogens potentially present in source waters to achieve the health outcome target set by regulators. The reference level of risk of 10^{-6} DALYs pppy included in the GDWQ is used in this document. Regulators may choose to adopt this as a target or alternatively can vary it depending on local circumstances, including overall burdens of disease.

As it is not realistic or possible to derive performance targets for all waterborne pathogens the practical approach is to derive targets for enteric bacteria, viruses and protozoa using representative reference pathogens for each group of organisms. The selection of reference pathogens should be based on a number of factors, including evidence of waterborne transmission, sensitivity to removal or inactivation by treatment processes and local conditions including prevalence of disease and associated source water characteristics (see Appendix 1). The reference pathogens used as examples in the GDWQ (WHO, 2017a) are *Campylobacter*, rotavirus and *Cryptosporidium*. However, the significance of rotavirus will be reduced over time by the development of a vaccine that will change the incidence and severity of disease outcomes from this pathogen (Gibney et al, 2014). Norovirus causes about 18% of acute diarrhoeal disease globally with similar proportions in high- and low-income settings (Lopman et al, 2015). As a result, norovirus is used as the reference pathogen for viruses in this guidance.

It has not been standard practice to identify a specific reference pathogen or calculate performance targets for helminths in drinking-water. Concentrations of helminths are relatively low in wastewater even in hyper-endemic regions (1000/L, Mara et al, 2010) and a 5-log performance target is required to meet a health outcome target of 10^{-6} DALYs pppy. Helminths are much larger than protozoa (40–90 µm compared with 4–6 µm for *Cryptosporidium*) which can be used as a conservative surrogate for physical removal of helminths.

The application of microbial performance targets involves the identification of appropriate combinations of treatment processes to achieve the LRVs (see Chapter 2). The treatment processes that are put in place have implications for operational monitoring, which should be implemented to demonstrate that the LRVs are being achieved, rather than direct pathogen monitoring. For example, maintaining low turbidity targets will demonstrate removal of protozoa (as well as helminths) (see Section 3.1).

5.1.1 Calculation of performance targets

The method for determining performance targets is presented in Appendix 1. Targets are calculated using the formula:

$$\text{Required log reduction} = \log \left(\frac{\text{concentration of the pathogen in source wastewater}}{\text{pathogen concentrations equivalent to } 10^{-6} \text{ DALYs pppy}}\right)$$

As shown in Appendix 1, pathogen concentrations equivalent to 10^{-6} DALYs pppy are:

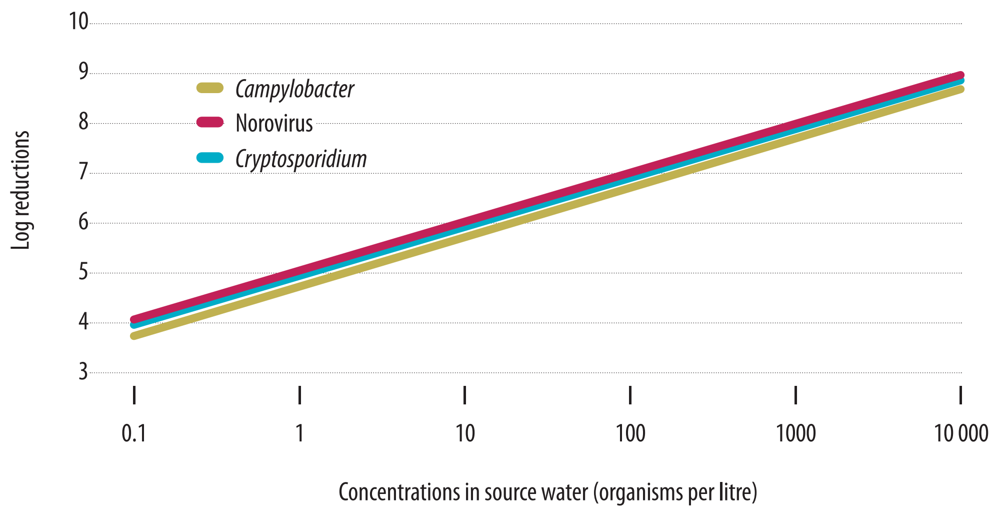
- enteric bacteria (*Campylobacter*) – 2.0×10^{-5} organisms/L
- enteric viruses (norovirus) – 1.1×10^{-5} PCR detectable units (PDU)/L
- enteric protozoa (*Cryptosporidium*) – 1.2×10^{-5} oocysts/L.

These concentrations were calculated using the method described in the GDWQ with modifications based on more recent information. These include the replacement of rotavirus with norovirus as a reference pathogen. The changes are discussed in more detail in Appendix 1. As noted in the GDWQ, pathogen concentrations equivalent to 10^{-6} DALYs pppy (10^{-4} to 10^{-5} per/L) are only used in calculating performance targets for treatment processes. They do not represent guideline values and are not intended to encourage pathogen monitoring in drinking-water which would be impractical and of little value for routine monitoring. Ensuring microbial safety of drinking-water, including that produced by potable reuse schemes, is based on online or frequent operational monitoring of control measures designed to meet required performance targets (Section 3.1).

Performance targets as a function of reference pathogen concentrations

As shown in the formula above, performance targets are proportional to the concentrations of pathogens in wastewater (Figure 5.1). This will be influenced by the prevalence of disease in communities which will vary in different countries and regions. Within countries, prevalence of some diseases can vary seasonally and will increase substantially in response to outbreaks. For these reasons performance targets should ideally be calculated by drinking-water suppliers using system specific data.

Figure 5.1 Log reduction requirements as a function of source water concentrations of pathogens



Default concentrations

In the absence of system specific data an alternative is to adopt default concentrations for selected reference pathogens based on published data. As discussed in Appendix 1, the following default concentrations can be used for untreated wastewater:

- 7000 *Campylobacter*/L
- 20 000 PDU noroviruses/L
- 2700 infective *Cryptosporidium* oocysts/L.

These default concentrations can be used in the formula above to calculate performance targets as shown in Table 5.1.

Table 5.1 Performance targets calculated from default concentrations of pathogens

	Pathogens		
	Enteric bacteria (*Campylobacter*)	Enteric viruses (noroviruses)	Enteric protozoa (*Cryptosporidium*)
Default concentration (per litre) in source wastewater	7000	20 000	2700
Log reductions[a]	8.5	9.5	8.5

[a] Rounded to nearest 0.5 log.

5.2 Chemical water quality targets

The GDWQ includes guideline values for a wide range of potential chemical contaminants in drinking-water, including naturally occurring chemicals, pesticides and industrial chemicals (WHO, 2017a). In order for derivation of a guideline value to be considered one of the following criteria must be met:

- There is credible evidence of occurrence of the chemical in drinking-water, combined with evidence of actual or potential toxicity.
- The chemical is of significant international concern.
- The chemical is being considered for inclusion or is included in the WHO Pesticide Evaluation Scheme.

While chemicals that could be specifically associated with discharges from municipal WWTPs have not been considered in setting guideline values, the existing rationale applies equally well to potable reuse. Guideline values are not required for chemicals present in trace amounts that are highly unlikely to cause health impacts. New guideline values should only be established for chemicals that meet the criteria specified in the GDWQ (WHO, 2017a). No new guideline values are proposed for potable reuse.

5.2.1 Derivation of guideline values

Two approaches are used for setting guideline values: one for threshold chemicals and the other for non-threshold chemicals (mostly genotoxic carcinogens). Threshold chemicals are those for which it is believed that there is a dose below which no adverse (toxic) effects will occur. For threshold chemicals, guideline values are calculated from tolerable daily intakes (TDI), derived from the NOAEL or LOAEL or the BMDL. Non-threshold chemicals are those for which there is a theoretical risk at any exposure. Guideline values are derived using mathematical models to project drinking-water concentrations associated with an upper bound of one additional case of cancer per 100 000 people consuming drinking-water for 70 years. These models are conservative, where the lower bound risk can be zero or below zero. The GDWQ describes how other upper bound risk benchmarks can be calculated (WHO, 2017a).

5.2.2 Contaminants of emerging concern

A recurring issue raised in association with potable reuse has been concern expressed over the broad range of chemical contaminants discharged into sewerage systems such as pharmaceutical residues, personal care products, household chemicals, engineered nanoparticles and steroidal hormones. It is often suggested that these contaminants are unique to potable reuse schemes, but they can also be present in any source waters that receive wastewater or industrial discharges. Water bodies that receive wastewater and industrial discharges may provide dilution that significantly reduces the concentrations of these contaminants. Most of these contaminants are not subject to specific regulation in drinking-water and do not have guideline values as they do not meet the risk-based criteria included in the GDWQ.

Pharmaceuticals provide a good illustration of a group of chemicals that have received attention in relation to drinking-water quality in general, and potable reuse in particular, due their known biological activity in humans. Numerous reports have shown that many pharmaceuticals can and do occur at trace concentrations in wastewater and subsequent receiving waters. However, a WHO review (WHO, 2012) concluded that in the absence of a specific local source, concentrations detected in drinking-water were very unlikely to cause significant health effects and that development of guideline values for inclusion in the GDWQ is not warranted. This includes antibiotics which have also been identified as a potential concern in providing triggers for development of antibiotic resistant microorganisms. If a specific source of pharmaceuticals is identified, screening values can be developed to support investigation of potential health risks (see below).

The review concluded that concerns over pharmaceuticals should not divert attention and resources from microbial pathogens and established chemical priorities such as lead and arsenic. The report also noted that conventional treatment processes such as chlorination can effectively remove 50% of pharmaceuticals investigated, while advanced treatment technologies, such as ozonation, AOPs (UV/H_2O_2 or ozone/H_2O_2), activated carbon and high pressure membrane filtration (RO and NF), can achieve higher removal rates (above 99%). Treatment applied in potable reuse schemes typically provides stronger barriers to pharmaceuticals, including antibiotics, than those in conventional drinking-water treatment plants.

Traditional wastewater treatment processes remove a high proportion of nanoparticles while processes used in advanced treatment, such as membrane filtration processes, are more effective in removing nanoparticles (Neale et al, 2012; Abbott Chalew et al, 2013).

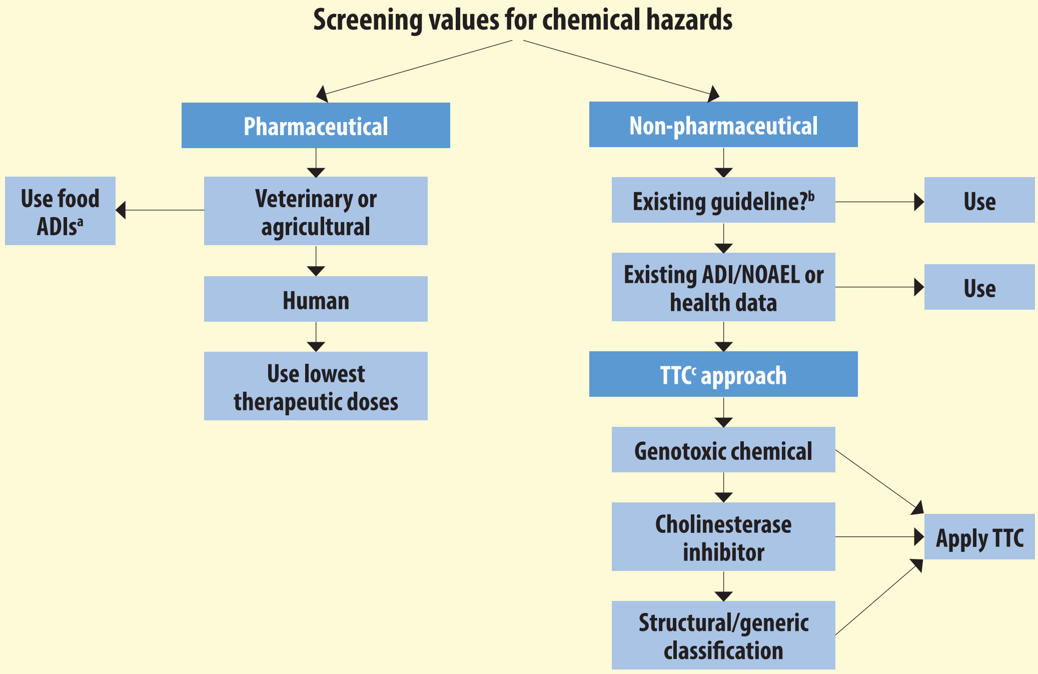
Screening values

The WHO review of pharmaceuticals in drinking-water noted that, in particular circumstances, where source water surveys indicate a potential for elevated levels of pharmaceuticals (e.g. presence of poorly managed discharges from manufacturing facilities), screening values could be developed as part of investigations into potential risks and the need for implementation of additional control measures. The most effective response following detection of an unacceptable source of pharmaceuticals is implementation of effective discharge controls. While screening values are useful indicators of potential risks they are not equivalent to guideline values as defined in the GDWQ.

Approaches for developing screening values, commonly using minimum therapeutic doses and conservative safety factors, have been developed for pharmaceuticals detected in wastewaters (Schwab et al, 2005; DWI, 2007; Snyder et al, 2008; NRMMC-EPHC-NHMRC, 2008; Bruce et al, 2010; WHO, 2012). These studies showed that there were considerable margins of safety between concentrations of pharmaceuticals in treated wastewater, surface waters and drinking-water and potential health impacts.

Screening values can also be developed for other chemicals of concern identified in particular circumstances. Where available, toxicological information can be used to derive screening values using conventional approaches (NRMMC-EPHC-NHMRC, 2008) (see Box 5.2). Where there are insufficient toxicological data to set a screening value by the conventional method, the threshold of toxicological concern concept can be used (Kroes et al, 2004; 2005; Munro et al, 2008). This model largely relies on carefully compiled toxicological databases of acute, subchronic and chronic NOAELs. The concept was originally developed to prioritize toxicity testing of food additives and food contact materials, but the methodology can be applied to other occupational and environmental settings, including drinking-water contaminants, for setting conservative screening or interim values until sufficient toxicological data are available to set guideline values where required (Rodriguez et al, 2007; NRMMC-EPHC-NHMRC, 2008).

Box 5.2 Approach for setting screening values for chemicals of concern in the Australian Guidelines for Water Recycling



In this framework conservative safety factors were applied. More details are provided in the Australian Guidelines for Water Recycling (NRMMC-EPHC-NHMRC, 2008).

[a] ADI = (Australian) acceptable daily intake levels. ADIs are developed for veterinary and agricultural chemicals that may produce residues in food.
[b] Existing guideline in this context means a guideline value developed by a country other than Australia.
[c] TTC = threshold of toxicological concern. The TTC approach was adapted from Kroes et al (2004; 2005).

Dieter (2014) proposed a variation of this approach. Based on extrapolation of toxicological evaluations from almost 200 evaluations by international agencies for substances found in drinking-water, Dieter proposed a five-step scale of health-related indication values ranging from 0.01–3.0 µg/L based on consumption of 2 L of drinking-water per day. The lowest values were for chemicals with genotoxic potential while higher values were for non-genotoxic chemicals. Exceedances of health-related indication values would prompt further investigation and a need for additional toxicological data to improve assessments. In these cases, the health-related indication values function as interim values prior to setting threshold of toxicological concern-based guideline values or traditionally set guideline values.

No matter which approach has been used, testing of wastewater, secondary treated wastewater and streams receiving discharges has shown that there are substantial margins of safety for most individual compounds, even prior to advanced treatment. In most circumstances, significant risks to human health from CECs are very unlikely through drinking-water supplies including potable reuse schemes (NRMMC-EPHC-NHMRC, 2008; DWI, 2007; Snyder et al, 2008; WHO, 2012; 2016a).

5.2.3 Chemical mixtures

No natural water contains only one chemical discretely. The reality is that all waters contain complex mixtures of natural and synthetic chemicals (of both organic and inorganic forms) in concentrations that vary greatly by location, season and even diurnally. Within wastewater, the mixture of chemicals is highly complex and often at much higher concentrations than would be found in non-wastewater impacted surface water and groundwater. The standard approach for determining chemical safety is based on developing guideline values for individual chemicals, generally without consideration of additive effects or potential synergistic or antagonistic interactions. In a limited number of cases guideline values account for chemical mixtures, such as trihalomethaness, microcystins, nitrate/nitrite and radionuclides, where an additive approach is recommended.

It is considered that the large margin of uncertainty incorporated into drinking-water guideline values through conservative application of safety factors (NRMMC-EPHC-NHMRC, 2008) is sufficient to account for potential interactions from low-dose exposures, which are expected to be limited at concentrations usually present in drinking-water (WHO, 2017a). Although there has been much discussion of the potential impacts of chemical mixtures, currently there is no scientifically based and regulatory acceptable methodology for carrying out risk assessments for chemical mixtures in source waters or drinking-waters. Further, significant knowledge gaps, complexity, limited practical experience and resource intensity, preclude this type of approach being systematically introduced into drinking-water standards at the present time (WHO, 2017c). As discussed in Section 3.2, the use of bioanalytical tools has been suggested as one approach to measuring toxicological activity in water. This approach would detect the activity of chemical mixtures as a whole, but these tools have not been developed to the point where they can be used in a regulatory context. Further work is being undertaken in this area.

If it is suspected that a number of toxicologically similar chemicals (i.e. with similar modes of action and/or end-points) are present in water, generally, an assumption of additivity is appropriate. In the absence of sufficient information on the mode of action of the individual components, the dose/concentration addition method is often used as a default in human toxicology chemical mixture assessments. Due to the limited evidence available, this includes a general assumption that interactions (synergism and antagonism) either do not occur at all or are small enough to be insignificant to the risk estimate (WHO, 2017a; 2017b).

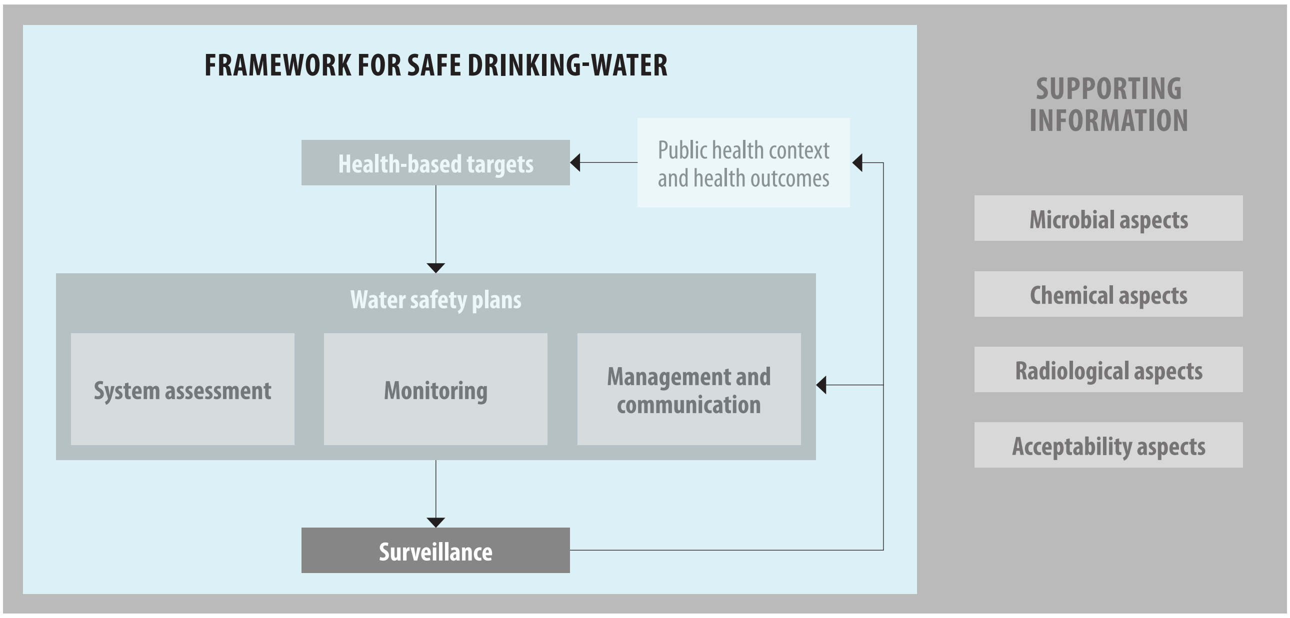
5.3 Radioactivity

The GDWQ provides screening levels of 0.5 Bq/L for gross alpha activity and 1 Bq/L for gross beta activity (WHO, 2017a). If a screening level is exceeded, specific radionuclides should be identified and their individual activity concentrations measured. The activity concentrations can be compared against the guidance levels for individual radionuclides included in the GDWQ (Chapter 9 and Annex 6). The GDWQ also describes how to aggregate the risks of the detected radionuclides.

The screening levels and guidance levels are based on the individual dose criterion of 0.1 mSv from one year's consumption of drinking-water, which is a conservative figure and below the International Basic Safety Standard's[5] recommendation that the highest individual doses received due to consumption of drinking-water do not exceed approximately 1 mSv y^{-1} (WHO, 2017a). The individual dose criterion represents an annual risk for radiation induced cancer of 5.5×10^{-6} per year. In general, radionuclides would seldom be a special concern in potable reuse because the concentrations are usually very low and natural terrestrial exposures are greater. The focus should be on ensuring that adequate controls are maintained on discharge of industrial and medical wastes containing radionuclides.

[5] The International Basic Safety Standards are the international benchmark for radiation safety and are sponsored by eight international organizations, including WHO. These standards are used in many countries as the basis for national legislation to protect workers, patients, the public and the environment from the risks of ionizing radiation.

6. REGULATIONS AND INDEPENDENT SURVEILLANCE



KEY MESSAGES

1. **The content of regulations should be consistent with those developed for other types of drinking-water supplies.**
2. **Development of a single set of regulations for drinking-water including potable reuse should be considered.**
3. **Implementation of the framework for safe drinking-water should be the focus of regulations.**
4. **Regulations should include or reference water quality standards and specify monitoring requirements and reporting of results.**
5. **Independent surveillance is essential to ensure appropriate design and implementation of WSPs and compliance with regulatory requirements.**
6. **Regulations need to identify roles and responsibilities of stakeholders, including regulators, drinking-water suppliers and wastewater management utilities (where appropriate).**

Regulation of drinking-water quality, irrespective of the source, plays an important role in protecting public health. Regulations for potable reuse, while recognizing the potential complexity of schemes, should be similar to those for other drinking-water supplies and development of a single set of regulations dealing with all sources should be considered. Regulations should:

- be consistent with the principles in the GDWQ (WHO, 2017a);
- provide clear direction to drinking-water suppliers on how safety can be achieved;
- define how compliance will be assessed and enforced;
- ensure communication between regulators, suppliers and consumers.

Provisions should be included to ensure application of the framework for safe drinking-water, including health-based targets, WSPs and surveillance (WHO, 2017a). Provisions could also be required to ensure implementation of SSPs where used (WHO, 2015a). This is more likely where wastewater and drinking-water treatment are managed by different entities. In addition, specific requirements should be included to deal with particular characteristics of potable reuse, such as microbial performance targets consistent with the use of wastewater as a water source, and the possible use of environmental or ESBs. This could include management of industrial discharges into municipal wastewater systems; discharge of treated wastewater into waterways and reservoirs; and injection or infiltration of treated wastewater into aquifers. In many jurisdictions, these specific issues may be dealt with by separate environmental protection or water resource legislation.

All relevant ministries and agencies should be involved or consulted in the development of regulations. These could include ministries with responsibilities for health, water, wastewater, water resources; drinking-water suppliers; agencies with responsibilities for wastewater collection and treatment; local government. Well-designed regulations support delivery of safe drinking-water and, importantly for potable reuse schemes, should foster community confidence in drinking-water quality and trust in regulators and providers.

6.1 Regulations

The aim of drinking-water regulations, including for potable reuse schemes, should be to ensure production and delivery of safe drinking-water to consumers. Regulations for potable reuse should align with principles described in the GDWQ and include provisions describing:

- responsibilities of drinking-water providers, wastewater management entities, regulatory agencies and other stakeholders;
- requirements for WSPs and SSPs;
- water quality standards;
- monitoring and testing requirements;
- reporting requirements during normal operation and in response to incidents and emergencies; and
- surveillance.

The scope of potable reuse regulations will be influenced by existing regulations dealing with wastewater management, environmental protection and water resource management. In some cases, existing regulations may need to be revised, for example regulations for existing WWTPs may need to be strengthened to provide greater assurance of performance of this component of potable reuse schemes. It is likely that administration, and perhaps augmentation of these existing regulations, will be undertaken by different agencies and these agencies will need to be consulted in drafting potable reuse regulations. Where appropriate, existing regulations should be cited.

6.1.1 Responsibilities

Regulations should identify the regulatory authority/authorities and their area of responsibility. In many countries drinking-water quality is regulated by the ministry of health, either acting alone or in combination with regional and local environmental health agencies. In some cases, environmental protection agencies can be the regulatory authority. Alternative models can also be developed.

Regulatory authorities are responsible for administering legislation and ensuring that all specified activities are undertaken and that all requirements are met. This includes monitoring compliance of drinking-water suppliers to relevant provisions. Regulations need to include powers that can be used by regulatory authorities to ensure compliance. These powers can include requiring remedial action where necessary, making decisions about the safety of drinking-water supplies, issuing public notifications when needed and applying penalties. The ability to apply penalties and sanctions is necessary but should only be used as a last resort.

Regulations will assign and describe specific functions to be undertaken by regulatory authorities. These can include setting and varying water quality standards, defining incident criteria and protocols, undertaking or monitoring surveillance, approval of testing laboratories and validation of treatment processes. Surveillance may be undertaken by the regulatory authority directly or may involve review and assessment of surveillance undertaken by third parties. An accreditation system should be established for surveillance officers and third-party auditors, where used.

Regulations should also identify the entities involved in the operation and management of potable reuse schemes and their responsibilities. The range of entities involved will be influenced by existing arrangements. For example, in some cases, wastewater management and drinking-water supply are undertaken by one agency (Seah & Woo, 2012) while in other cases responsibilities can be split (Angelotti & Grizzard, 2012) (see Box 6.1).

Box 6.1 Multiple agency involvement in potable reuse

The Occoquan Watershed (Virginia, USA) provides an example of multiple agency involvement in potable reuse. In this case, a coordinating mechanism was established through a state regulation (the Occoquan Policy) to manage water quality in the Occoquan drinking-water reservoir including inputs of treated wastewater. The policy mandated the Upper Occoquan Service Authority (UOSA) to provide collection and treatment of wastewater and the Occoquan Watershed Monitoring Program (OWMP) to monitor the watershed and receiving reservoir. The OWMP provides oversight and recommendations to UOSA, the drinking-water utility (Fairfax Water) and state regulatory agencies (Angelotti & Grizzard, 2012).

Drinking-water suppliers are responsible for appropriate treatment and delivery of safe drinking-water to consumers. They are responsible for applying sound management practices and quality control through implementation of WSPs. Regulations should provide direction on what this will entail and describe functions to be undertaken by drinking-water suppliers. This should include requirements to notify regulatory agencies when a supplier knows or suspects a drinking-water supply may be unsafe.

Where wastewater and drinking-water are managed by separate entities, direction should be provided on the functions and responsibilities of these entities. Continuous coordination of activities undertaken by wastewater management entities and drinking-water providers is essential to assure ongoing production of safe drinking-water from potable reuse schemes.

6.1.2 Water safety plans and sanitation safety plans

Regulations should reinforce that good management requires the implementation of WSPs. Regulations may also specify implementation of SSPs for municipal WWTPs, particularly where wastewater and drinking-water treatment are managed by different entities. Regulations should specify the basic content of WSPs and SSPs based on components described in the WSP and SSP manuals (Bartram et al, 2009; WHO, 2015a). Regulations should specify frequency of WSP and SSP audits, requiring approval or auditing of WSPs and SSPs (if used) prior to commencement of supply and regularly thereafter to ensure that the WSPs and SSPs remain effective.

6.1.3 Water quality standards

Water quality standards are the mechanism for formalizing application of health-based targets (Chapter 5). Water quality standards should either be listed in regulations or incorporated by reference to a separate document, such as a set of national drinking-water guidelines or standards based on the GDWQ. If a reference document is cited, the regulations should identify which targets are relevant. Water quality standards could include:

- **Microbial performance targets:** These can be set as default pathogen concentration reductions (described as LRVs) based on default source wastewater concentrations identified by the regulator. An alternative is to require operators of potable reuse schemes to determine performance targets from system specific pathogen concentrations (see Section 5.1). Where water suppliers are required to determine these targets, standards would need to specify the health outcome target (e.g 10^{-6} DALYs pppy), and describe the methods for collecting system specific data (e.g. reference pathogens, numbers of samples) and for calculating targets (see Appendix 1). Some of these details could be included in associated codes of practice.
- **Numerical water quality targets for chemical and radiological parameters:** These should be the same as those adopted for other drinking-water supplies.

Inclusion of critical limits for operational parameters could also be considered. Examples include filtered water turbidity and disinfectant doses or Ct values. If critical limits are included it should be clear that they only apply when certain treatment processes are selected. Regulations should not include mandatory requirements for specific types of treatment process.

6.1.4 Testing and reporting requirements

Regulations should define testing requirements for parameters, sampling frequencies, sampling locations and nature of testing (e.g. field or laboratory testing). Testing requirements should include consideration of operational and verification monitoring. Regulations for operational monitoring can include specific requirements for individual treatment processes such as transmitted UV light, chlorine Ct values, filtered water turbidity and membrane integrity testing. Frequencies will vary depending on the type of testing and practical considerations, for example filtered water turbidity will typically be measured continuously online while membrane integrity could be measured on a daily basis (USEPA, 2005). Further details on operational monitoring are provided in Section 3.1.

Regulations for verification monitoring should describe the frequency of testing for parameters listed in water quality standards and sampling locations. Further details on verification monitoring are provided in Section 3.2.

Procedures for approving testing laboratories should be included in regulations. This could be based on compliance with established accreditation systems. If accreditation systems have not been established the regulatory authority should consider establishing competency standards. These should include criteria relating to approved methods and the skills and training of analysts.

Reporting of results is an essential component of regulations. Provisions should deal with reporting to regulatory authorities of:

- Routine results including the manner and frequency of reporting.
- Non-compliance with water quality standards and other incidents that may threaten drinking-water safety. Time limits for reporting should be identified. For example, it could be specified that non-compliance with critical limits should be reported within one hour of detection. One option could be a requirement to develop approved incident protocols incorporating incident criteria, reporting requirements and contact details of emergency personnel (Chapter 4).

6.1.5 Surveillance

Independent surveillance is one of the three core components of the framework for safe drinking-water (WHO, 2017a) and describes the external and periodic reviews to assess management and production of safe drinking-water. Surveillance should assess compliance with the requirements of the framework for safe drinking-water, including the design and implementation of WSPs and SSPs through regular audits. It should cover the whole of the drinking-water system from sources of water to treatment processes, storage reservoirs and distribution systems, through to supply to consumers. For potable reuse schemes, it should include consideration of the source of wastewater (domestic, agricultural, industrial) and barriers to entry of toxic industrial waste and other preventable sources of hazards. Surveillance can include independent testing of water quality.

Testing undertaken by surveillance agencies should complement verification testing undertaken by the drinking-water supplier. Results of testing undertaken as part of surveillance should be reported to the drinking-water supplier. In this case, the surveillance agency would need to have the capacity to undertake sampling and have access to appropriate field testing equipment and accredited laboratories. When regulators do not have this capacity, periodic testing undertaken by a third party could be considered as an alternative. Irrespective of which approach is taken to water quality testing, all results should be reviewed as part of auditing of potable water supplies. If water quality testing is included as part of surveillance, regulations should specify the range of parameters, frequency of testing and sampling locations, and should be published in a publicly accessibly manner.

Reporting requirements will also need to be specified. It is important that outcomes of surveillance activities, including water quality results (where testing is undertaken), identification of significant faults and the need for remedial actions, are reported promptly to the drinking-water supplier and, in the event of third-party auditing, to regulatory authorities.

Whether surveillance is undertaken by the regulatory agency or a third-party auditor reporting to the regulatory agency, there should be legislated powers to ensure access to sites and documentation generated by drinking-water suppliers and wastewater management utilities.

Water safety plan and sanitation safety plan audits

WSP and SSP audits are independent assessments of the completeness, adequate implementation and effectiveness of WSPs and SSPs. Periodic audits should be undertaken at regular intervals, following substantial changes to water sources or infrastructure and following significant incidents. Given the complexity of potable reuse, it should be expected that proponents have high levels of expertise and the capacity to develop well-designed and comprehensive WSPs and SSPs.

Informal audits to assist in the development of WSPs and SSPs prior to commencement of supply should not be necessary (WHO, 2015b). Audits should be regarded as constructive processes that can confirm good practice; assist wastewater management entities and drinking-water suppliers in ensuring effective operation of WSPs and SSPs; and, where necessary, identify how operation of WSPs and SSPs can be improved. They should not be regarded as processes designed solely as fault finding exercises or to penalize drinking-water suppliers. Audits should examine records and documentation to ensure that WSPs are well designed and have been maintained and implemented as described in the plans.

Where more than one agency or organization is involved in the operation and performance of the potable reuse scheme (e.g. separate wastewater management and drinking-water supply agencies), audits should determine whether all components of the scheme have been included in WSPs and SSPs. Where multiple plans have been developed, audits should ensure that they are consistent and coordinated. In addition, audits should determine whether relevant agreements and contracts between agencies have been identified, mechanisms to ensure communication have been established, and obligations relating to operation and monitoring have been met.

Specific guidance on performing periodic audits is provided in A Practical Guide to Auditing Water Safety Plans (WHO, 2015b). The guidance developed for WSPs can be adapted to SSPs. Audits should include an assessment of WSP and SSP documentation, including whether it:

- is complete, logical and up to date;
- is easily accessible, understood and used by staff; and
- includes a record-keeping system for all activities described in the WSP and SSP, including monitoring.

Audits should ensure that safety plans accurately describe and address all components of the potable reuse system, including sources of wastewater (e.g. domestic, agricultural, industrial, etc.), the wastewater system, waste discharge controls, treatment processes, environmental or engineered buffering storages (if used), blending waters (i.e. other sources of drinking-water) and distribution systems.

Regulations should specify the frequency of audits, procedures for directing suppliers to take remedial action if required, and provisions for follow-up audits to monitor implementation.

Responsibilities and accreditation

Surveillance officers and third-party auditors, if used, need to be suitably qualified to undertake surveillance. Accreditation systems for auditors, based on recognized qualifications and experience, should be established. Guidance on auditor qualifications, training and certification is provided in A Practical Guide to Auditing Water Safety Plans (WHO, 2015b).

Where surveillance is undertaken by third-party auditors the regulatory agency should review the content and recommendations included in audit reports. Where there are adverse findings or recommendations for remedial action the regulatory agency should ensure that appropriate responses are implemented and remedial action is completed. These responses should be checked by a follow-up audit.

Communication of results

It is essential that results of surveillance activities are communicated to:

- drinking-water suppliers and where applicable to other agencies such as wastewater management utilities;
- regulatory agencies in the event of third-party auditing;
- consumers; and
- local authorities where the surveillance agency is a centralized government agency.

Surveillance requires the cooperation and assistance of drinking-water suppliers and wastewater management utilities and requires good communication prior to the event. This communication should be maintained during an audit. Auditors should provide a verbal report to drinking-water suppliers through an exit meeting before leaving the site of an audit. The report should include an assessment of the WSP and SSP, the safety of the drinking-water supply, and any recommendations for immediate remedial action and longer term improvements. Knowledge or suspicion that a potable reuse supply is unsafe must be communicated to the drinking-water supplier immediately. Failures of the water supplier to detect and report such faults should be investigated. Auditors should provide a report of their findings to the drinking-water supplier within a reasonable timeframe (e.g. one month). The drinking-water supplier should be given the opportunity to review and comment on the report before it is finalized to clarify any misunderstandings or provide further information. Where independent water quality testing is undertaken as part of surveillance, results should be communicated as soon as possible to the drinking-water supplier together with any recommendations for follow-up testing, further investigations or remedial action.

Similar communication should be undertaken when surveillance is undertaken by third-party auditors. In addition, audit reports should be provided to the relevant regulatory agency. Knowledge or suspicion that a potable reuse supply is unsafe must be communicated to the relevant regulatory agency immediately.

In some cases, responsibilities for regulation and surveillance may be shared between a centralized government department and regional and local health authorities. It is important that the central agency and the relevant regional and local authorities receive and share the same audit reports and associated outcomes. Communication systems need to be established to ensure that this occurs.

The community has the right to know the outcome of audits. Outcomes should be shared with consumers either by providing access to the audit report or by providing an agreed summary of the report.

Implementation of surveillance results

Outcomes and recommendations from audits or based on water quality results (where included in surveillance) need to be implemented. This can take the form of a range of actions to improve the design and implementation of WSPs and SSPs. Auditors should provide an indication of the significance of faults or gaps in WSPs and SSPs to enable drinking-water suppliers and wastewater management utilities to prioritize implementation of remedial action and improvement programmes. This could involve classifying faults using a grading system (e.g. minor, moderate or major). Recommended actions and improvements should be documented, included in the WSP and SSP, and progress assessed in the next audit. Where significant faults are identified, the auditor should identify when the next audit will occur. Normally this will be prior to the next routine audit.

6.1.6 Random inspections and responses to evidence of unsafe water

Regulations should include powers for regulatory authorities to inspect drinking-water supplies and associated documentation and to take or require water quality testing. This is required to enable action to be taken in the event of evidence of unsafe water through, for example, detection of waterborne illness or clusters of consumer complaints.

6.1.7 Communities and consumers

Consumers have a right to information about the quality of drinking-water supplies. A major community concern in regard to the provision of safe drinking-water from wastewater is human error. While there may be confidence in the science of providing safe drinking-water, there is concern about the risks inherent in the human operation of water supply systems (Nancarrow et al, 2009). However, trust in the authorities (regulators and water supply providers) can have a major effect on lessening community perceptions of risk. Transparent and open information and reporting will build community trust in the authorities.

Therefore, regulations should incorporate provisions for information and regular reporting to consumers on:

- The performance of potable reuse systems which include summaries of results accompanied by interpretations of what the results mean.
- Results and information in response to reasonable requests delivered within a specified time.

Reporting can take the form of annual water quality reports published within a specified time (e.g. three months) after the end of a calendar or financial year.

Consumers have an expectation that they will be informed if drinking-water supplies are unsafe. Where a decision is made by the regulatory authority that a potable reuse supply is unsafe and represents an unacceptable risk to public health it should be communicated immediately to consumers. The responsibility and methods of delivery for this type of communication need to be established before it is required. The content of notifications and the methods of delivery should take into account the diversity of consumers and their access to communication services (e.g. print media, television, radio and electronic media).

6.1.8 Periodic review of regulations

Over time there can be changes that impact on regulations. These can be organizational, scientific or technical and can include emerging hazards, new evidence leading to variation of standards, new treatment methods, different operational procedures or changes to operational monitoring methods and parameters. Experience, including lessons from surveillance outcomes, can also identify ways that application of regulations can be improved. Regulations and standards should be subject to periodic review to ensure they remain current and effective. Processes for review should be clearly understood and should involve consultation with all stakeholders, including consumers.

6.2 Existing policies, regulations and guidelines on potable reuse

There are limited examples of policies, regulations and guidelines dealing with potable reuse schemes. When the Windhoek scheme was developed in the 1960s and upgraded in 2002 there were no standards available so self-regulation was introduced and enforced through a management agreement (see Box 6.2). However, this is changing and there is increasing advocacy in policy documents and papers for potable reuse (Tchobanoglous et al, 2011; 2015; Dahl, 2014; ATSE, 2013; Olivieri et al, 2016) (Appendix 3) and initial development of regulations has commenced.

California has established regulations for IPR via groundwater recharge (CDPH, 2014) and is in the process of developing criteria for IPR via surface water augmentation. The feasibility of developing criteria for DPR is also under consideration. In a limited number of cases regulations have been developed. In Queensland, potable reuse is included in drinking-water legislation.[6]

In addition to the development of specific guidelines for potable reuse, it is common practice for established schemes to be subject to drinking-water guidelines. In Singapore, the aim for the NEWater scheme is compliance with guideline values specified in the GDWQ (WHO, 2017a) and USEPA drinking-water standards (USEPA, 2014). In the USA, water supplied from potable reuse schemes is subject to drinking-water quality requirements specified in the Safe Drinking-water Act[7] (Tchobanoglous et al, 2015) as well as possible state requirements.

Box 6.2 Windhoek, Namibia – self-regulation

When the first Goreangab reclamation plant was developed in the 1960s there were no standards for potable reuse. As a result, in 1973, the Reclamation Technical Subcommittee identified requirements to ensure the safety of potable reuse. These included requirements relating to wastewater quality, control of industrial discharges, treatment, operational control, verification of water quality and oversight by the Director of Public Health.

When the new Goreangab reclamation plant was developed, although Namibian Guidelines for Drinking-water had been approved in 1988, there was no reference to use of treated wastewater. As a result, the City of Windhoek applied self-regulation by developing standards for the new plant from existing international standards and guidelines for drinking-water quality. These included a comprehensive set of numerical water quality standards, including intermediate and final water standards, each with target and absolute values. Multiple barriers were incorporated in the new plant to remove contaminants or substances to specified levels and to ensure compliance with the standards. The standards are enforceable under the private management agreement under which the plant is operated. For additional information see Appendix 3.

[6] Queensland Water Supply (Safety and Reliability) Act available at: https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/W/WaterSupSRA08.pdf

[7] Information on the Safe Drinking-water Act is available at: https://www.epa.gov/sdwa

7. THE ART OF PUBLIC ENGAGEMENT

KEY MESSAGES

1. **The success of potable reuse depends on the ability to gain public confidence and trust.**
2. **Information is paramount and should be made readily available to the public so they understand the background, context and available options.**
3. **When dealing with difficult questions associated with health, safety and environmental impacts of potable reuse, it is essential to be open and transparent.**
4. **Consider terminology – words matter. Use positive terms and avoid terminology that is not well understood.**
5. **Key stakeholders should be engaged, including the media and opinion leaders in the political, social and community spheres.**
6. **Where possible consider establishing visitor centres and organizing plant tours as learning experiences.**
7. **Online communication is crucial. Social media should be leveraged to tell the potable reuse story in a positive and engaging manner.**

Central to the success of any potable reuse project is the ability to gain public confidence and trust through a productive, two-way engagement process with key stakeholders. There is ample research and documented case studies worldwide that support this. A sustained and comprehensive public communication plan that addresses the health, safety and quality concerns throughout the various stages, from planning to implementation, is an essential tool to advance the success of projects.

Effective engagement involves an intimate understanding of water and how humans rely on it. It involves careful selection of terminology to inform communities about the contaminants found in water and how treatment technology can remove them to produce safe drinking-water. The goal is not to obtain public acceptance but to generate expanded and meaningful interactions with the community – interactions that produce understanding.

In the absence of understanding about water use and reuse, a sustainable water future will remain out of reach. There is no magic formula that yields public acceptance, but it has become clear that strong, imaginative information programmes and early and consistent two-way engagement are necessary to open the door to more sustainable water management. This is the art of attaining the level of public understanding that is essential to the success of any potable reuse programme.

This chapter outlines the key components of the potable reuse public engagement plan, and how it can be used to build public confidence and trust. With differing political and social needs and circumstances from country to country and city to city, an engagement programme for potable reuse cannot be a one-size-fits-all approach. However, there are some key aspects that need to be considered and included for an effective engagement programme. These can be adapted to suit the needs of different communities. The list is by no means exhaustive, but it covers key factors that have led to successful public engagement.

7.1 Engagement programme

7.1.1 Availability of information

Information is paramount. Information needs to be made readily available to the public in a suitable form to support understanding of potable reuse proposals. The first step in any engagement plan is to provide information readily to the public so that they understand the background, context and options available. Understanding rather than acceptance should be the goal. An uninformed public cannot have informed opinions and is vulnerable to having knowledge vacuums filled with misconceptions. Although not all members of the community will have the time or inclination to absorb the information provided, the knowledge that it is available is reassuring and extremely important to effective engagement.

Those who are interested should be able to gain sufficient knowledge, which may help to reassure those they know who have doubts about the safety of potable reuse.

Access to information is therefore important to enable the subsequent dialogue between the utility and the stakeholders to take place in a productive manner. Table 7.1 illustrates the key information areas that should be communicated to the public. Information about available water supplies should be provided well in advance of discussion about potable reuse. Table 7.2 summarizes useful communication tactics to consider when presenting messages on potable reuse.

Table 7.1 Communication of information to the public

Key information area	Communication plan
Water supply options available	When formulating a water resources plan, it is important that problems of water shortages are clearly communicated and that all options are identified and evaluated. If the community thinks that some options have been overlooked, they will not trust the process. The goal of an engagement programme is not to promote potable reuse, but to ensure that it is understood, so that it can be considered a suitable option for augmenting drinking-water supplies.
Planned vs unplanned potable reuse	The public is generally aware of the natural water cycle, but some are not aware of the practice of discharging treated or untreated wastewater into rivers (unplanned potable reuse) for use by downstream communities as sources of drinking-water.
Contaminants (pathogens and chemicals) in drinking-water from potable reuse systems	The communicators must be prepared to answer technical questions about the nature of the contaminants (including pathogens and chemicals) in water. They need basic knowledge to be able to explain how control measures, including treatment technologies, can be used in multiple-barrier processes to inactivate or minimize contaminants. Community health officials and physicians should be included in the outreach process.
Technology	Advanced treatment processes must be clearly explained in simple terms so that the public of all ages are able to fully comprehend what the technology can do and how contaminants in water are removed.

Table 7.2 Tactics for communicating messages on potable reuse

Message	Communication tactics
Make potable reuse familiar – showcase the experience of other countries and cities	To make potable reuse familiar, it is useful to present case studies that clearly demonstrate how many communities are already drinking "reused water" without always being aware of it. Research has shown that communicating the success of potable reuse projects elsewhere helps to create a sense of familiarity. Telling the stories of early adopters helps quell fears. Their stories should emphasize the need for the water, the benefit of the projects, the fundamentals of treatment and the safety/reliability of the product water.
Quality, not history	Terminology and messages must focus on the quality of the water, not the history of where the water has been, i.e. not its source as wastewater or how it has been used, but what the water can safely be used for. Explain how monitoring ensures safety. The main concern of the public is the safety and quality of drinking-water from potable reuse. For reassurance, it is important to emphasize the amount of monitoring and tests that will be undertaken. Emphasizing reliability and monitoring is part of the hallmark of quality. Explain that the water will meet appropriate national and international standards and that the scheme has the support of the relevant regulatory agency.
Benefits of potable reuse	Because supplies of wastewater are not subject to the variability of weather, potable reuse is a sustainable, drought-proof source of water that has an invaluable role to play in strategies to address the global water crisis. Potable reuse has benefits for the environment because it reduces discharges of nutrients into waterways. The technology is proven to be effective and well understood and can be affordable, considering some of the alternatives. Wastewater is the only source of water that increases with population.

7.1.2 Information plan

When dealing with difficult questions associated with the health, safety and environmental impacts of potable reuse it is essential to be open and transparent. An open and interactive channel for information sharing is important to demonstrate that the utility or agency values the views of the public, and is involving the public in the implementation process, as opposed to going ahead with the decision without seeking any feedback. One approach is to provide a website and social media tools that present information and allow the community to engage by asking questions. It is important to have mechanisms to deal with unexpected questions from the community. A plan needs to be in place to provide rapid responses by a trusted expert.

Clear and consistent messages are important in communication plans. The key messages should build confidence in potable reuse as a viable and sustainable water supply option and communicate its key benefits. Examples of key messages are outlined below.

- Potable reuse is a safe, reliable and sustainable source of drinking-water.
- Using recycled water is good for the environment.
- Potable reuse is a valuable and drought-proof water supply source capable of strengthening water supply resilience, especially against weather extremities like dry spells and droughts.

Messages alone are not sufficient – communication plans must include information about the approaches to show the pollutants in water and the advanced technologies that remove them. Stakeholders need to be able to see that water gets cleaner and cleaner as it goes through the various treatment processes. Information included in Box 7.2 showcases messages that are memorable and have visual appeal.

Consider terminology – words matter. Use positive, non-stigmatizing terms and avoid terminology that is not well understood. The meaning of words is closely linked to the feelings they convey; they can influence behaviour and attitudes. Although there are numerous dictionaries and glossaries that aid in defining water reuse terms, most are written for engineers, scientists and other water professionals and thus require some technical knowledge. Effective engagement involves careful selection of terminology to inform communities about the contaminants found in water and how treatment technologies can remove them to produce safe drinking-water.

This can be more challenging in countries with religious practices where water has specific religious and historically spiritual connotations. It is imperative to use terms that are consistent with the significance of water to people of various faiths, while still being mindful to use terms that do not stigmatize reuse. Consistency is also important, for example, there are several terms used to refer to treated wastewater. Agreement should be reached on a single positive term, or phrasing that is appropriate to the country and its setting.

Even though words like "wastewater" and "sewage" are internationally recognized terms within the water industry and are used in this guidance and other WHO texts on wastewater reuse (WHO, 2006), they have a negative connotation that reminds people of their source, and their use adds to the psychological aversion. It is worthwhile to consider replacing technical terms with words that are neutral and factual. For example, "wastewater" and "sewage" can be referred to as "used water". This also better reflects treated wastewater's true value as a resource within the water cycle. Water can be used and reused, similar to the natural water cycle – it is not wastewater to be "thrown away." "Water reclamation plants" or "used water treatment plants" can be used in place of "sewage treatment plants" or "WWTPs" as these plants are not merely treating sewage, but are now part of the process that reclaims the used water for further reuse. Treated sewage could be referred to as "purified water".

7.1.3 Communication strategy

Identify and engage with key stakeholder groups such as media and opinion leaders in the political, social and community spheres so that they can help to garner more public support. Key to the campaign to win public confidence and acceptance is the way an organization relates to and communicates with its various groups of stakeholders. This must be done in a meaningful, thoughtful, and trustworthy manner, so that the public can see the proposal and its issues in context and be able to consider and discuss the points made by its advocates and opponents.

Opinion leaders are important because they influence the attitudes, beliefs, motivations and behaviour of others. They influence community opinions by raising awareness, persuading others, establishing or reinforcing norms, and leveraging resources. They usually are highly visible in the community and have a defined constituency, which increases the likelihood that others will adopt their behaviour. It is therefore vitally important that considerable attention be paid to ensure that opinion leaders are aware of the need to increase water supply sources and are knowledgeable about the technical processes associated with water management.

Political, religious, medical and university leaders can serve as key opinion leaders because of their visibility and the influence they exert on the community and nation they serve.

Engaging the media. Another critical stakeholder group is the media, as they often act as the watchdog for the community and question authorities on their plans and policies. A well thought out media plan is needed to get journalists to understand and potentially support a project. Bringing the media on a tour of the potable reuse facility and giving them a first-hand look at the advanced technology employed in the process will aid their understanding of potable reuse. Designating a primary contact point for the media will help to ensure prompt replies are provided.

Independent expert testimony is an effective way to provide answers to difficult and challenging questions on health, safety and quality. Having a panel of international and local water experts in the various related fields of engineering, biomedical sciences, chemistry and water technology to provide independent expert testimony and address health, safety and quality issues is an effective way to provide answers to frequently asked questions. As specialists in their own areas of research, who are also familiar with water recycling projects elsewhere, experts have the credibility and are best suited to address safety and health concerns – the public's top priority. The expert panel's reports can be captured on video and shown in a visitor centre, on agency websites and reported by the media. Independent scientific panels can also garner news coverage that the agency may not.

Employ visitor centres, demonstration centres, online (virtual) and plant tours as learning experiences. Visitor centres, demonstration centres, and tours provide an appealing information dissemination alternative that can frequently become a multi-objective destination. Even online virtual tours provide insight and images that can be game changing for audiences unfamiliar with advanced technologies. They are an alternative to public meetings and even to the typical classroom experience because they can provide spaces and exhibits that are novel, stimulating, evidence-rich, multisensory, and fun. Visitor centres can vary in size and expense. They can be in a stand-alone building, a building associated with a treatment plant or public spaces. Visitor centres are ideal for school tours.

Present water tasting opportunities, where possible. There is nothing more convincing than the public trying the product. Recycled water can be bottled in attractive packaging so that the public can sample how pure the water is. The water samples can be distributed at events, tours and at visitor centres. Tasting of the water samples by opinion leaders, including politicians and other trusted community leaders, can build trust and reinforce the safety of the product.

Online communication is a key tool for spreading information. Leverage social media channels to tell the potable reuse story in a fun and engaging manner. Social media is an increasingly important platform for sharing information and seeding conversations. Social media is a space where people share their everyday lives. Communication efforts need to engage in the spaces where people communicate and create opportunities for engagement and interactivity. Conversational approaches and the use of visual imagery rather than just factual messaging and language resonate with digitally literate people. Using short, sharp animations and videos that can be shared in the social media space can enhance understanding. Engaging in online conversations is also critical to demonstrate the willingness to listen to and respond to negative comments that are raised in social media forums in a timely, positive and helpful way. There are many guidance documents on the use of social media that can be consulted when crafting an education and engagement strategy.

Water utilities should continue to explore how best to communicate and connect with various demographics in their communities using social media platforms. Dialogue can run both ways, and efforts to reach and engage hard-to-reach audiences are expanded by developing a broader communication platform that goes beyond traditional mediums of print, radio, email and television.

7.2 Preparing information to attract and hold attention

To be effective, an education/communication plan must be designed so that it attracts and holds attention. Information must appeal to people who have a range of learning preferences – some learn by hearing, others prefer to read either in a printed form or on their computer. All benefit from seeing the processes in action and it should always be remembered that the use of humour is a powerful way to gain attention and stimulate the memory. A utility's communications toolbox should include a range of products, including:

- informative factsheets
- infographics
- animations
- videos, virtual tours and documentaries
- interactive computer programmes
- media outreach programmes and visits to water reuse facilities
- social media channels
- visitor centres, demonstration centres, displays and plant tours
- water tastings.

7.3 Evaluating information and engagement programmes

Information/communication programmes should be evaluated, not only for the impact of their terminology and messaging but also for their ability to attract and hold attention. Pre- and post-surveys can be very helpful in determining and measuring whether educational experiences are having an impact. Evaluation can be used as a planning tool; building an evaluation phase into the very beginning of a project or programme will ensure that it happens. Finally, it is important to realize that education and engagement to promote change can take time and should be continued. Consistency is essential; it is advisable not to start and stop outreach efforts for political expediency. An evaluation programme will allow the utility to determine whether messages are being understood and reinforced. Because the education/communication programme is about changing behaviour, the evaluation process will help determine if it is succeeding and inform the design of new communication techniques. There are various techniques for evaluation, such as gathering responses pre- and post-experiences in a visitor space or online.

It is important to understand that not everyone has comparable knowledge and experience with potable reuse. An effective evaluation programme will help to identify how a specified education/engagement experience uniquely affects an individual's attitude about potable reuse.

In the absence of understanding about water use and reuse, a sustainable water future will remain out of reach. There is no panacea or magic formula that yields public acceptance, but it has become clear that strong, imaginative information programmes and early and consistent two-way engagement are powerful and effective strategies – strategies necessary to open the door to more sustainable water management. This is the art of attaining the public understanding that is the critical ingredient to the success of any water reuse programme.

7.4 Case studies and additional information

In some instances, officials have called off plans to implement potable reuse after they faced public opposition and outcry. Although these projects were well designed with sound engineering principles, supported by extensive laboratory tests to ensure water quality, the lack of a well thought out public communications programme combining science/technology and art/social science considerations to garner public support dealt them a huge blow. Headlines like "toilet to tap," that play on the psychological and emotional aspects of the human mind, were shown to cloud logical reasoning. The result was public resistance to potable reuse. But slowly, things are changing. In recent years, more cities are implementing schemes, fuelled in part by prolonged dry spells and droughts. Appendix 4 provides four case studies where the water reuse project has either succeeded or failed because of public communications:

- Singapore: NEWater, nothing new
- Orange County Water District, California, USA: One programme, multiple benefits
- Toowoomba, Queensland, Australia: No to water recycling
- San Diego, California, USA: Where persistence paid off.

Additional information on community engagement and sources of educational material are provided in Boxes 7.1 and 7.2.

Box 7.1 Additional information and guidance documents

Demoware (2015). Trust in reuse: Review report on international experiences in public involvement and stakeholder collaboration. http://demoware.eu/en/results/deliverables/deliverable-d5-2-trust-in-reuse.pdf/view

Dolnicar S, Hurlimann A, Nghiem LD (2010). The effect of information on public acceptance – The case of water from alternative sources. Journal of Environmental Management. 91(6):1288–1293.

Fielding SK and Roiko AH (2014). Providing information promotes greater public acceptance for potable recycled water. Water Research. 61: 86–96.

Johnson S and Macpherson L (2014). Stream 3 products evaluation report. Australian Water Recycling Centre of Excellence, Brisbane, Australia. www.water360.com.au

Kearnes M, Motion J, Beckett J (2014). Australian water futures: Rethinking community engagement. Report of the National Demonstration, Education and Engagement Program, Australian Water Recycling Centre of Excellence and the University of New South Wales. November 2014. www.water360.com.au

Kunreuther H and Slovic P (1999). Coping with stigma: Challenges and opportunities. Risk: Health, Safety & Environment. 10(3):269–280.

Lohman LC (1987). Potable wastewater reuse can win public support. In: Proceedings of Water Reuse Symposium IV, Denver, Colorado, 2–6 August. AWWA Research Foundation.

Macpherson L and Slovic P (2011). Talking about water: Vocabulary and images that support informed decisions about water recycling and desalination. Alexandria (VA): WateReuse Research Foundation.

Macpherson L and Snyder S (2013). Downstream: Context, understanding, acceptance: Effect of prior knowledge of unplanned potable reuse on the acceptance of planned potable reuse. Alexandria (VA): WateReuse Research Foundation. WRF-09-01.

Millan M (2015). One glass at a time. Helping people understand potable reuse. A flexible communication plan for use by public information professionals. Derived from: Model communication plans for increasing awareness and fostering acceptance of direct potable reuse. Alexandria (VA): WateReuse Research Foundation. https://watereuse.org/water-reuse-101/fact-sheets/

Millan M, Tennyson P, Snyder S (2015). Model communication plans for increasing awareness and fostering acceptance of direct potable reuse. Alexandria (VA): WateReuse Research Foundation.

Ruetten J (2004). Best practices for developing indirect potable reuse projects: Phase I report. Alexandria (VA): WateReuse Research Foundation.

Shaukat F (1981). Philosophy of water reuse in Islamic perspective. Desalination. 39:273–281.

Slovic P (2009). Talking about water – and stigmatizing it. Decision Research report no. 15-01.

Tchobanoglous G, Cotruvo J, Crook J, McDonald E, Olivieri A, Salveson A, Trussell RS (2015). Framework for direct potable reuse. Alexandria (VA): WateReuse Research Foundation.

Water Environment Federation (2015). The effective water utility professional, Chapter 2, "Communication."

Box 7.2 Educational materials

Water360: The Australian Water Recycling Centre of Excellence initiated the Water360 partnership to contribute to an ongoing sharing of information and knowledge about potable reuse as a safe, reliable and cost-effective option for water security. Water360 education products are designed to be flexible and adaptable to a diversity of geographic settings and cultural contexts. The materials are particularly useful because they can be adapted to incorporate local content and context, be combined in various ways, and link to school curricula or existing utility educational materials and programmes. The materials are also adaptable to multiple display platforms such as kiosks, long-form documentaries, video walls, interactive screens, social media and phone and tablet applications.

Water360 includes a global connections map. The map emphasizes the need for potable reuse, the benefits of reuse, its reliability and treatment processes. Video stories are told in various ways, with people from all walks of life in each area – from plant managers to citizens.

www.water360.com.au

From waste-d-water to pure water: This booklet by Jenifer Simpson is a primer for those beginning to look at recycled water, how it is made, its quality and types of uses. The booklet also brings a clear perspective to the risks associated with reuse. It describes what is put into water and wastewater, how it is taken out again, and how to make sure that it has been taken out. Fully illustrated with diagrams, cartoons and photos, the guide explains the sophisticated and efficient technologies available so that readers can understand and learn to trust them. The booklet introduces the star rating system for water quality that describes the quality of water as it becomes progressively cleaner – the more stars, the more opportunities to use the precious resource.

http://newwaterresources.com/wp-content/uploads/2015/09/From-waste-d-water-to-pure-water_condensed.pdf

WateReuse Association: The WateReuse Association has a range of materials, including several adapted from their collaboration with the Australian Water Recycling Centre of Excellence. The products include:

- Water: Think and drink – six 2.5-minute animations;
- the global connections map with frequently asked questions from experts – an interactive computer programme; and
- science and visual process animations – 12 animations.

https://watereuse.org/water-reuse-101/videos/
https://watereuse.org/water-reuse-101/global-connections/

WateReuse Research Foundation: The foundation prepared a video slideshow, entitled "Downstream," that explains potable reuse in the context of the urban water cycle. The video explains that most of the world's population drinks from rivers and streams that have received discharges from upstream users. The image-rich presentation shows that water can be purified to be made drinkable again and shows that water reuse is the key to a sustainable future. "Downstream" is available in English and Spanish on YouTube.

https://www.youtube.com/watch?v=GVm-d-zOxJs

The foundation also produced "The ways of water," an animation presenting an overview of the many human interventions in the water cycle. The animation looks at the benefits of some key water provision options including DPR. The animation presents the urban water cycle and water purification; produced with social media in mind. It is available in English and Spanish on YouTube.

https://www.youtube.com/watch?v=RwrYFJEJSQ0

8. CONCLUSIONS

8.1 Summary of key messages

Potable reuse is a practical source of drinking-water that should be considered when developing new drinking-water supplies or when expanding or replacing existing supplies. Major advantages of potable reuse are that it is largely a climate-independent source of water that takes advantage of locally available and collected wastewater for sustainable use of water. In addition to providing an ongoing source of drinking-water, potable reuse also reduces undesirable environmental impacts of wastewater discharges.

As shown in Table 1.2 and demonstrated by the case studies provided in Appendix 5, interest in potable reuse is growing and it is expected that the number of schemes will continue to increase in response to expanding populations and climate pressures. As demonstrated in this guidance, the scientific and technological basis for implementing potable reuse has been established. Well-designed potable reuse schemes, managed in accord with the framework for safe drinking-water, including WSPs, will produce safe drinking-water. In this respect, potable reuse is no different from other sources of drinking-water. The principles and health-based targets described in the GDWQ (WHO, 2017a) apply to potable reuse in the same way as they do to all drinking-water supplies and generally there is no justification or requirement for additional targets, including additional guideline values, to be applied to potable reuse.

While the GDWQ (WHO, 2017a) applies to the design, management and operation of potable reuse schemes there are a number of aspects of potable reuse that require particular attention compared with other drinking-water systems. These include:

- The potential involvement of multiple agencies, including separate entities responsible for wastewater management and production of drinking-water (Chapters 1 and 6).
- The importance of coordinating activities associated with wastewater management and production of drinking-water and communication between operators (Chapters 1 and 6).
- The potential use and coordination of WSPs and SSPs (Chapters 1 and 6).
- The high concentrations of pathogens and the broad range of chemical hazards potentially present in wastewater (Chapter 2).
- Heightened public interest in CECs, including pharmaceuticals, natural hormones, personal care products and trace industrial compounds (Section 2.2).
- Rapid variability in source water quality and flow (diurnal, daily, seasonal, etc.) (Chapter 2).
- The use of complex multiple-barrier treatment trains which can include processes such as advanced oxidation and multiple forms of disinfection. Collectively these complex systems provide large reductions of potentially hazardous microorganisms and chemicals (Chapter 2).
- The possible use of environmental and engineered storage buffers (Chapter 2).
- Impacts of blending of different sources of drinking-water on distributions systems, particularly for DPR (Chapter 2).
- Increased need for public engagement and education (Chapter 7).

While potable reuse is a practical source of drinking-water in many circumstances, potable reuse schemes are typically complex and proponents need to have sufficient resources and capabilities for successful implementation. Availability of appropriately trained and skilled operators is an essential requirement. Other key issues and associated conclusions include:

- Wastewater contains high concentrations of enteric pathogens. As a result, production of microbially safe drinking-water requires setting of relatively high performance targets (default targets; minimum 8.5-log reduction of enteric bacteria, 9.5-log reduction of enteric viruses and 8.5-log reduction of enteric protozoa) (Chapter 5). They do not represent guideline values but rather, have implications in identifying control measures and in particular, combinations of treatment processes (Section 2.5.2).
- While there tends to be greater interest in CECs, such as pharmaceuticals and personal care products, the concentrations are generally low and generally do not warrant setting of new guideline values. The guideline values described in the GDWQ (WHO, 2017a) are sufficient in most circumstances. Where source water surveys indicate a potential for elevated levels of a chemical without a guideline value (e.g. due to poorly managed discharges from manufacturing facilities) screening values could be developed as part of investigations into potential risks and the

need for implementation of additional control measures (Section 5.2).

- Control measures should be applied from collection of wastewater to the delivery of drinking-water. Control measures need to be validated and generally, LRVs are based on challenge testing and sensitivities of operational monitoring, particularly where operational monitoring is relied upon for demonstrating ongoing performance of treatment processes (Sections 2.5 and 2.6).
- While operational monitoring follows the principles described in the GDWQ, continuous monitoring linked to SCADA systems with automatic alarms for deviation from critical limits will be common (Section 3.1).
- The content of regulations should be consistent with those developed for other types of drinking-water supply. Development of a single set of regulations for drinking-water including potable reuse should be considered (Chapter 6).
- The success of potable reuse depends on the ability to gain public confidence and trust. Information should be made readily available to the public so they understand the background, context and available options. Key stakeholders, including the media and opinion leaders in political, social and community spheres, should be engaged (Chapter 7).

8.2 Case studies

Two sets of case studies are provided to illustrate how issues associated with potable reuse have been addressed. Case studies on community engagement are provided in Appendix 4, while successful implementation of potable reuse schemes is illustrated in Appendix 5, with seven case studies from Australia, Namibia, Singapore and the USA. The case studies on implementation include examples of potable reuse with and without the use of environmental buffers.

8.3 Knowledge gaps and future research

There are a number of knowledge gaps including:

- **Improved operational monitoring methods are required to support validation of MBR and RO, including operational parameters or procedures that can be used to identify low level failures.** As described in Section 2.6, pilot trials and laboratory tests have demonstrated that RO can achieve greater than 6-log reductions of microbial pathogens but operational monitoring lacks sensitivity and reduces the log credits that can be claimed to 2–4 logs. For MBR, operational monitoring parameters that correlate with pathogen log reductions have not been identified.
- **Additional data on concentrations and infectivity of pathogens in wastewater.** A large proportion of wastewater pathogen monitoring is not published. Additional quality controlled data would enable identification of more accurate default values for calculation of performance targets. It would be particularly useful if regional or climate specific data could be identified. The reference pathogen used in this guidance for enteric viruses is norovirus, however, there is no practical method to routinely identify and enumerate human infectious norovirus. Culture methods developed using B cells (Jones et al, 2015) and stem cells erythroids (Ettayebi et al, 2016) may lead to future development of a routine assay. The availability of such a method would improve the accuracy of microbial risk assessments and improve the setting of performance targets required to achieve safe drinking-water.
- **Rapid testing to boost the effectiveness of engineered storages.** The use of engineered storages in DPR can at least in part compensate for the incident response time provided by environmental storages in IPR. However, the size and detention time of water in engineered storages is limited by practical and economic considerations. The effectiveness of these storages would be enhanced by the development of additional rapid testing procedures that can be used to identify treatment failures and water quality non-compliance prior to water being discharged into distribution systems. This could include development of rapid assays for enteric pathogens or indicator organisms (e.g. coliphages).
- **Development of biological assays that can be used singly or in combination to demonstrate potential impacts on public health.** As discussed in Box 3.3, more than 100 assays have been developed to test various types of biological activity in water. However, understanding the relevance of these assays, including the translation of results into assessments of public health risk, has not been achieved and uncertainty remains regarding the role of bioanalytical tools in a regulatory context. Further research is required to address these gaps.
- **Improved understanding of incident occurrence and management in potable reuse schemes.** While the aim is to operate potable reuse schemes without failure or incidents it is inevitable that faults will occur. These incidents do not necessarily lead to a significant public health risk occurring providing appropriate remedial action is implemented in a timely fashion. Most incidents and responses go unreported. It would be useful if more were reported to enable lessons to be shared and learned.

Appendix 1. Reference pathogens and performance targets

A1.1 Introduction

Microbial safety is usually defined in terms of achieving performance targets expressed as log reductions of reference pathogens selected to represent enteric pathogens potentially present in source waters. Log reductions are calculated using quantitative microbial risk assessment and disease burdens to translate the probability of disease into potential human health impacts (WHO, 2016b).

A1.2 Selection of reference pathogens

Due to the different characteristics of the major groups of enteric pathogens, it is standard practice to identify separate reference pathogens for bacteria, viruses and protozoa.

Selection of reference pathogens is based on a number of properties including:

- waterborne transmission established as a route of infection;
- sufficient data available to enable a quantitative microbial risk assessment to determine the probability of disease following exposure of consumers to reference pathogens, including: dose–response relationships and infection to illness ratios;
- data available on impacts of disease (prevalence and severity of symptoms) to enable calculation of disease burden in DALYs;
- occurrence in source waters;
- persistence in the environment; and
- sensitivity to removal or inactivation by treatment processes.

The GDWQ (WHO, 2017a) identifies a number of potential reference pathogens, including *Vibrio cholerae*, *Campylobacter*, *E. coli* O157, *Salmonella*, *Shigella*, rotavirus, norovirus, enterovirus, *Cryptosporidium* and *Giardia*. Selection of reference pathogens may vary between different countries and should be based on consideration of prevalence and severity of disease and source water characteristics. The reference pathogens used as examples in the GDWQ (WHO, 2017a) are *Campylobacter*, rotavirus and *Cryptosporidium*. While rotavirus remains a significant contributor to waterborne disease the use of rotavirus as a reference pathogen has been complicated by the development and use of a rotavirus vaccine which is changing the incidence and severity of disease outcomes from this pathogen (Gibney et al, 2014). Norovirus, which fulfils the requirement of a reference pathogen, is a suitable alternative. Norovirus causes about 18% of acute diarrhoeal disease globally with similar proportions in high- and low-income settings (Lopman et al, 2015) and is a common cause of waterborne outbreaks (Guzman-Herrador et al, 2015; Moreira et al, 2016). Two-dose response models, a beta poisson and a fractional poisson model, have been published for norovirus (Teunis et al, 2008; Messner et al, 2014) and a disease burden has been determined (Gibney et al, 2014). The fractional poisson model characterizes hosts as being completely susceptible or completely immune, with infection probability based on the probability of exposure to at least one virus particle or aggregate. In this document, the traditional dose dependent beta poisson model has been adopted (Table A1.1). The outcomes of using the two models are similar.

A1.3 Calculation of performance targets

Performance targets can be calculated using the formula:

$$\text{Required log reduction} = \log\left(\frac{\text{concentration of the pathogen in source wastewater}}{\text{pathogen concentrations equivalent to } 10^{-6} \text{ DALYs pppy}}\right)$$

The concentrations of reference pathogens equivalent to 10^{-6} DALYs pppy (DALYd) are calculated as shown in Table A1.1 using:

- quantitative microbial risk assessment to determine the likelihood of disease arising from exposure to reference pathogens (WHO, 2016b); and
- the disease burden from single cases of disease.

Table A1.1 Calculation of concentrations of reference pathogens equivalent to 10^{-6} DALYs pppy (DALYd)

	Reference pathogen		
	Campylobacter	Noroviruses	*Cryptosporidium*
Dose–response parameters	$\alpha = 0.145, \beta = 7.58$[a] Approx. beta poisson	$\alpha = 0.0044$, $\beta = 0.002$[b] Exact beta poisson	$r = 0.2$[a]
Low-dose formula[c]	$P_{inf} = \frac{\alpha}{\beta}.d$	$P_{inf} = \frac{\alpha}{\alpha+\beta}.d$	$P_{inf} = r.d$
Probability of infection per organism (P_{inf})	0.019	0.69	0.2
Probability of illness per infection ($P_{ill/inf}$)	0.3[a]	0.7[d]	0.7[a]
Probability of illness per organism ($P_i = P_{inf} \times P_{ill/inf}$)	0.0057	0.48	0.14
Disease burden (DB)[d] (DALYs per case)	2.4×10^{-2}	5×10^{-4}	1.7×10^{-3}
DALY d = $\left(\frac{10^{-6}}{P_i \times DB \times 365}\right)$(organisms per L drinking-water)[e]	2.0×10^{-5}	1.1×10^{-5}	1.2×10^{-5}

[a] GDWQ (WHO, 2017a) and WHO (2016b).
[b] Messner et al (2014) with correction as noted in Van Abel et al (2016).
[c] Low-dose approximations from FAO/WHO (2003) and Petterson et al (2006).
[d] Teunis et al (2008), Seitz et al (2011), Frenck et al (2012), Atmar et al (2014).
[e] 365 represents annual consumption of unboiled drinking-water based on 1 L per day.

A1.4 Derivation of default pathogen concentrations

In the absence of system specific pathogen data, an alternative approach can be to use default pathogen concentrations generated from published assessments of untreated wastewater quality. Preferably this should be derived from regions with similar distributions and prevalence of disease.

This approach was adopted in the Australian Guidelines for Water Recycling (NRMMC-EPHC-NHMRC, 2008), which identified default values for concentrations of reference pathogens in untreated wastewater using data from influents to large metropolitan WWTPs. The Australian guidelines used 95th percentile concentrations to take into account observed variability in concentrations of reference pathogens and increases observed during outbreaks of disease. These concentrations were used to calculate minimum performance targets to meet the health outcome of 10^{-6} DALYs pppy (Table A1.2).

Table A1.2 Australian performance targets calculated from default concentrations of pathogens

	Pathogens		
	Enteric bacteria (*Campylobacter*)	Enteric viruses (noroviruses)	Enteric protozoa (*Cryptosporidium*)
Default concentration in wastewater (per litre)	7000	8000	2000
Log reductions	8.1	9.5	8

Source: NRMMC-EPHC-NHMRC (2008).

The State of California has adopted a similar approach to determine conservative performance targets from maximum reported concentrations of enteric pathogens in wastewater to reduce the level of risk to below an acceptable level of 10^{-4} infections pppy (Table A1.3).

Table A1.3 Californian performance targets calculated from default concentrations of pathogens

	Pathogens		
	Enteric viruses	*Cryptosporidium*	*Giardia*
Maximum wastewater concentration (per litre)	10^5	10^4	10^5
Tolerable concentrations per litre to meet 10^{-4} infections pppy	2.2×10^{-7}	1.7×10^{-6}	6.8×10^{-6}
Log reductions	12	10	10

Source: Adapted from Olivieri et al (2016).

Adaptations of these approaches can be used to derive performance targets for *Campylobacter*, norovirus and *Cryptosporidium* using default values as described below.

Campylobacter

There is limited data for culturable *Campylobacter* in wastewater; Soller et al (2016) reported a range of 900–40 000 organisms per L from results published in 1993. The Australian data (95th percentile 7000 organisms per L) is more recent and can be used as a default value (NRMMC-EPHC-NHMRC, 2008).

Enteric viruses

Ideally, for reference pathogens there should be a method available to determine concentrations of potentially viable and infectious particles. Although there are genome-based methods (e.g. using PCR-based molecular amplification) for norovirus (and rotavirus), there are no practical methods for routinely monitoring infective particles in environmental samples. Culture methods developed using B cells (Jones et al, 2015) and stem cell erythroids (Ettayebi et al, 2016) may lead to development of a routine assay but such an assay is not yet available.

There are two alternative approaches that can be used to determine or estimate norovirus concentrations. The first is to use published concentrations derived using PCR. A meta-analysis of published data (566 results) from 12 studies, including results from inlets to 42 WWTPs, calculated a mean concentration of 3.9-log PDU per L (95% confidence interval: 3.5–4.3) (Pouillot et al, 2015). Concentrations detected varied between treatment plants and demonstrated a general seasonality consistent with prevalence of disease (Pouillot et al, 2015).

A significant limitation in using data generated using PCR is the lack of a consistent relationship between PDU and infectious virus particles (Rodriguez et al, 2009; Jofre & Branch, 2010). Genome concentrations can be much higher than concentrations of infectious particles in wastewater and drinking-water sources (Choi & Jiang, 2005; Lodder & de Roda Husman, 2005; de Roda Husman et al, 2009; Rutjes et al, 2009; Lodder et al, 2010).

A second approach is to use culture-based methods to measure abundant virus species as surrogates for norovirus. Candidates include culturable mammalian orthoreoviruses (reoviruses) and adenoviruses, which have been identified as useful indicators for enteric virus concentrations in wastewater (Fong et al, 2010; Betancourt & Gerba, 2016; Mosher et al, 2016). Both are environmentally robust and relatively abundant in wastewater (Fong et al, 2010; Hellmer et al, 2016; Betancourt & Gerba, 2016). Adenoviruses include a number of serotypes that collectively cause a wide range of infections, with types 40 and 41 the main causes of enteric illness (WHO, 2017a), while the human disease significance of reoviruses is unclear, it is a common enteric virus (Betancourt & Gerba, 2016). Neither adenovirus or reovirus meet the requirements of a reference pathogen due to insufficient data being available to enable calculation of disease burdens in DALYs as shown in Table A1.1.

Culturable reoviruses were detected in concentrations up to 12 000 MPN[8] per L in a nine-year study by Sedmak et al (2005) (107 samples) of wastewater in Milwaukee, USA, while adenoviruses were detected in concentrations up to 20 000 MPN per L (92 samples) from wastewater in Australia (Deere & Khan, 2016). The concentrations detected in Australia are similar to those reported in Soller et al (2016) (range 56–6900 infectious units per L). Sedmak et al (2005) detected lower concentrations of adenovirus (and enterovirus) in wastewater.

There is not a large difference between the maximum concentrations of culturable reoviruses (Sedmak et al, 2005) and adenoviruses (Deere & Khan, 2016) and the upper limit of the 95th percentile credible interval for norovirus of 20 000 PDU from the meta-analysis by Pouillot et al (2015). As norovirus is the reference pathogen used in this guidance, the concentration of 20 000 PDU per L has been selected as a default value.

[8] MPN = most probable number determined by a culture-based method.

Cryptosporidium

Concentrations of *Cryptosporidium* vary widely between WWTPs and during outbreaks of disease. In one recorded outbreak, concentrations of infectious oocysts in wastewater increased between 10- and 40-fold during an outbreak (King et al, 2017). Maximum concentrations from 282 samples collected from nine Australian WWTPs were between 242–42 667 oocysts per L (95th percentiles 150–5460 oocysts per L) (Deere & Khan, 2016). All concentrations were determined using immunofluorescence and confirmed by 4',6-diamidino-2-phenylindole staining and differential interference contrast microscopy using the same standard method including correction for recovery (USEPA, 2012b). These results are consistent with those published elsewhere (0.3–50 000 oocysts per L; Yang et al, 2015; Soller et al, 2016).

While the standard method provides an indication of viability it does not determine human infectivity of detected oocysts. A separate investigation has demonstrated that between 7 and 44% of potentially viable *Cryptosporidium* oocysts detected in untreated wastewater are capable of initiating human infections (King et al, 2017). Applying a conservative value of 50% infectivity to the highest 95th percentile result of 5460 oocysts per L from Deere and Khan (2016) provides a default concentration of 2700 infectious *Cryptosporidium* oocysts per L.

Default concentrations and associated performance targets

Default concentrations of reference pathogens in untreated wastewater and associated minimum performance targets to meet an upper limit of 10^{-6} DALYs pppy are summarized in Table A1.4. The data used to select the default values are relatively conservative compared with that used for drinking-water (WHO, 2017a), which recommends the use of arithmetic means and reflects the poor quality of source wastewater. The default concentrations should only be used in the absence of system specific data.

Table A1.4 Default concentrations of reference pathogens and associated performance targets

	Pathogens		
	Enteric bacteria *(Campylobacter)*	Enteric viruses (noroviruses)	Enteric protozoa *(Cryptosporidium)*
Default concentration in wastewater (per litre)	7000	20 000	2700
Log reductions[a]	8.5	9.5	8.5

[a] Rounded to the nearest 0.5 log.

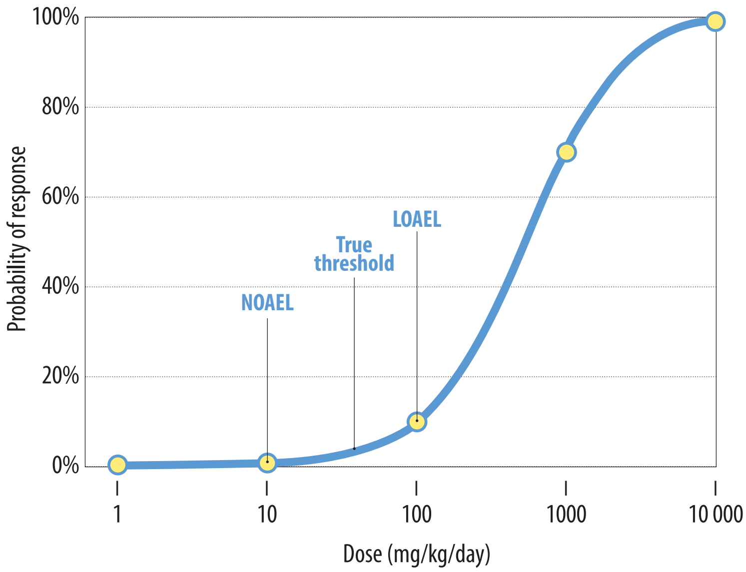
Appendix 2. Determining chemical guideline values

Two approaches are used for determining guideline values for "threshold" and "non-threshold" chemicals.

A2.1 Threshold chemicals

An example of a dose–response curve for a threshold chemical is presented in Figure A2.1 These types of curves are developed by experiments on animals (generally with very high concentrations of chemicals) to determine the relationship between the daily administered dose of a chemical as a function of body weight in milligrams per kilogram per day (mg/kg/day) leading to an established incidence of biological effects in the exposed population. From this (hypothetical) dose–response curve, it can be observed that a dose above 10 000 mg/kg/day resulted in toxicity to roughly 100% of the exposed population. Equally, it can be observed that there exists a dose (around 10 mg/kg/day) below which no "response" may be expected. That is, there is an identifiable "safe dose", known as the "threshold' dose".

Figure A2.1 Example of a dose–response curve for a "threshold chemical" contaminant



Toxicological investigations for non-carcinogenic ("threshold") studies are usually designed to enable the identification of either the highest dose at which no adverse effects are observed (NOAEL) or the lowest dose at which adverse effects are observed (LOAEL). NOAELs and LOAELs are conventionally determined in units of milligrams of the substance per kilogram of body weight per day (mg/kg/day).

The TDI for a chemical is then calculated from the animal test data after including adjustments to account for sources of variability and uncertainty. Uncertainty factors are applied to account for extrapolation of animal studies to human impacts (interspecies), variability amongst the human population (intraspecies) and uncertainties derived from incomplete toxicological databases such as the use of subchronic studies to derive chronic effects or the use of a LOAEL in place of a NOAEL. Each of these uncertainty factors are normally applied as a value of either 10 or 3, up to a suggested maximum product of 3000 (Ritter et al, 2007). Where uncertainty factors exceed 1000, guideline values determined in the GDWQ are designated as provisional due to the relatively high level of uncertainty (WHO, 2017a). Excessively large uncertainty factors in risk assessments are undesirable, may include redundant elements and lead to overly conservative default based calculations. Factors in the region of 100 are more desirable when an appropriate database is available. As an alternative to the use of uncertainty factors, chemical specific adjustment factors based on the use of quantitative toxicokinetic and toxicodynamic data can be used when available, to derive TDIs.

Increasingly, the preferred approach for the derivation of a TDI includes using the BMDL. When appropriate data are available, BMDLs are used as alternatives to NOAELs (IPCS, 1994) to use the whole of the dose response data.

The TDI can be calculated from a NOAEL, LOAEL or BMDL using the following equation:

$$TDI = \frac{\text{NOAEL or LOAEL or BMDL}}{\text{UF and/or CSAF}}$$

Where:

NOAEL = no-observed-adverse-effect-level
LOAEL = lowest-observed-adverse-effect-level
BMDL = lower confidence limit on the benchmark dose
UF = uncertainty factor
CSAF = chemical specific adjustment factor

The guideline value is then derived from the TDI as follows:

$$GV = \frac{TDI \times bw \times P}{C}$$

Where:

GV = guideline value
bw = body weight (default assumption for adult body weight is 60 kg)
P = fraction of the TDI allocated to drinking-water to take account of exposure from other sources such as food
C = daily drinking-water consumption (default assumption for an adult is 2 L/day)

A2.2 Non-threshold chemicals

In the case of compounds considered to be genotoxic carcinogens, guideline values are often determined using a mathematical model. Although several models exist, the linearized multistage model is generally adopted. Other models are considered more appropriate in certain cases. These models lead to calculation of a "cancer slope factor" (CSF), in which cancer risk per lifetime daily dose is given in inverse exposure units of $(mg/kg/day)^{-1}$. The hypothetical carcinogenic risk then is assumed to be linearly proportional in the low-dose range to the level of exposure to the chemical, with the CSF defining the gradient of the dose–response relationship as a straight line, projecting from zero exposure-zero risk. A sharper gradient, defined by a higher CSF, indicates a more potently carcinogenic chemical leading to increased cancer risk for any identified level of exposure.

The CSF for a specific carcinogen may be determined from human epidemiological studies or (more commonly) from chronic animal carcinogenicity assays. The CSF can be used to calculate the projected upper bound probability of increased cancer incidence (over a background cancer risk) over a person's lifetime (usually considered as 70 years) – the so-called "excess lifetime cancer risk" associated with a particular level of exposure.

In the GDWQ, WHO applies a tolerable level of risk of 1 in 100 000 or 10^{-5}. This is the excess lifetime cancer risk as a result of exposure to the chemical in drinking-water. The guideline value is then derived from an identified tolerable excess life time cancer risk level as follows:

$$GV = \frac{ELCR \times bw}{CDF \times C}$$

Where:

ELCR = estimated upper-bound excess lifetime cancer risk (applied by WHO at 10^{-5})
bw = body weight (default assumption for adult body weight is 60 kg)
CSF = cancer slope factor determined for the chemical $(mg/kg/day)^{-1}$
C = daily drinking-water consumption (default assumption for an adult is 2 L/day)

The assumption of the absence of a toxicological threshold for many carcinogenic end-points (including mutagenicity and genotoxicity) is well entrenched in chemical risk assessment, but is not universally accepted and is increasingly problematic (Nielsen et al, 2008). It is, in fact, likely that there are thresholds for a number of genotoxic effects. Furthermore, the low-dose extrapolation for non-threshold toxicological calculations is often across many orders of magnitude from the effects observed in experimental animals to established tolerable risk levels for humans. This extrapolation introduces significant uncertainties in the determination of acceptable exposure levels. In addition, it should be noted that the concentration associated with this risk is usually based on the upper 95% confidence interval of the calculation; the actual risk is likely to be much lower and may even be zero. It cannot be used to determine the number of cancer cases that will result from this exposure.

Appendix 3. Policies, regulations and standards

A3.1 Windhoek, Namibia

A3.1.1 Old Goreangab reclamation plant

During the latter part of the 1960s, the first Goreangab reclamation plant was developed without a set of standards for drinking-water produced from treated wastewater. Existing acts (Water Act 1956, Public Health Act 1919) did not refer to potable reuse although the Water Act did include a provision allowing for a local authority with jurisdiction over sewage disposal to use wastewater treated in accordance with standards to be used for any purpose approved by the minister. The first guidelines used were adopted from a publication by Stander and Van Vuuren (1969), which for chemicals provided criteria for potability, health hazards, toxicity, and as indicators of pollution. These were used in conjunction with International Standards for Drinking-water (WHO, 1963).

In the absence of ratified guidelines or standards for treated wastewater, the Reclamation Technical Subcommittee in 1973 identified the following requirements to ensure safety of potable reuse:

1) The treated wastewater used as raw water had to comply with a certain minimum standard.
2) The treatment processes employed for reclamation had to be approved.
3) Each unit had to be operated according to its operational guideline. When not complying, water had to be recycled from that unit to the inlet or to be wasted.
4) Operational test results had to be conducted on a four-hourly basis.
5) If routine bacteriological tests indicated satisfactory operation and control of the plant, then the water was acceptable.
6) Virology tests had to verify water quality.
7) Robust water quality test results were required to verify compliance of raw water and treatment steps.
8) All light industries with a measurable discharge would be monitored by the pollution control programme to determine the composition of the discharge. Heavy industrial waste was diverted to a separate industrial wastewater treatment site.
9) The Director of Public Health was given the authority to inspect the reclamation plant at any time and to stop production if it did not comply with any required standards or guidelines (Reclamation Technical Subcommittee, 1973).

A3.1.2 New Goreangab reclamation plant

Namibian Guidelines for Drinking-water were approved by the Cabinet of the Transitional Government in 1988. Once again, no reference was made to treated wastewater. In the absence of enforceable guidelines and standards, the City of Windhoek applied self-regulation by adopting standards from international drinking-water standards for the design of the new Goreangab reclamation plant. The approach remained that specific processes were to be incorporated with the specific purpose of removing or reducing concentrations of specific contaminants. For this new plant, however, specific water quality standards were prescribed, and to reach these requirements, multiple barriers were incorporated to remove hazards to specified levels.

In devising standards for the new plant, the following standards and guidelines were considered:

- Guidelines for the Evaluation of Drinking-water for Human Consumption (1991), Department of Water Affairs, Namibia (Namibian Guidelines, 1991)
- Potable Water Quality Criteria (Rand Water, 1994)
- WHO Guidelines for Drinking-water Quality (WHO, 1993)
- The National Drinking-water Standards and Health Advisories USEPA (USEPA, 1996)
- The European Community Guidelines for the use of water for human consumption (80/778/EWG) (1980 and 1994 draft) (EC, 1980)
- A guide for the planning, design and implementation of a water reclamation scheme (Meiring & Partners, 1982).

From these, a comprehensive set of standards were devised (Table CS1.2), including intermediate and final water standards, each with target and absolute values. The standards are enforceable under the private management agreement under which the plant is operated.

The 1988 Namibian Water Guidelines for Drinking-water were still applicable in 2016. The Namibian Water Resources Management Act 2013 empowers the minister to issue regulations, but a proposed new drinking-water standard has not been finalized.

A3.2 United States of America

Indirect potable reuse is included in the 2012 Guidelines for Water Reuse (USEPA, 2012a). The guidelines contain broad recommendations for IPR and describe combinations of treatment processes, water quality criteria, monitoring requirements and a two-month retention period in receiving waters (environmental buffers).

The framework for DPR (Tchobanoglous et al, 2015) reviews applicable USA regulations and summarizes microbial and chemical criteria for DPR. Microbial criteria developed by California (see below) and a National Water Research Institute (NWRI) expert group include minimum log reductions of 12-log for enteric virus, 10-log for enteric protozoa (*Cryptosporidium* and *Giardia*) and 9-log for total coliforms. The framework includes discussion of source control programmes, treatment technologies and treatment trains, achievable log reductions, process monitoring, facility operation including operator training and residuals management.

A3.2.1 California

Regulations were adopted in 2014 for the replenishment of groundwater by surface spreading or subsurface injection. The regulations include criteria for:

- public consultation;
- pathogen reduction requirements (12-log enteric virus, 10-log *Cryptosporidium* oocyst and 10-log *Giardia* cyst reduction) based on achieving an upper limit annual risk of infection of 10^{-4} per person;
- inclusion of a minimum of three treatment processes for each pathogen;
- the design of RO and advanced oxidation used to control chemicals of concern for subsurface injection;
- soil-aquifer treatment, retention times and dilution;
- process and water quality monitoring; and
- an operations plan identifying procedures for facility operation, maintenance and incident responses.

The feasibility of criteria for IPR via surface water augmentation and DPR is under investigation (as of 2016). California regulators have mechanisms to approve DPR in the absence of adopted criteria on a case-by-case basis should a community require this option to deal with a drought emergency.

A3.2.2 Texas and New Mexico

Guidelines for DPR have been prepared for the New Mexico Water Department (NWRI, 2016) and the Texas Water Development Board (TWDB, 2015). The Texas Commission on Environmental Quality has identified baseline targets of 8-log enteric virus removal, 5.5-log *Cryptosporidium* removal and 6-log *Giardia* removal from conventionally treated wastewater. Since these targets apply to treated wastewater and not untreated wastewater, which was the starting point for the Californian and NWRI criteria, the finished water quality is likely to be similar.

A3.3 Australia

Guidelines for drinking-water augmentation (potable reuse) (NRMMC-EPHC-NHMRC, 2008) were developed during the Australian millennium drought (2000–2010). The guidelines combine features of the GDWQ (WHO, 2017a), the Australian Guidelines for Water Recycling (NRMMC-EPHC-AHMC, 2006) and the Australian Drinking Water Guidelines (NHMRC-NRMMC, 2011). Key features include:

- A focus on risk management plans (similar to WSPs).
- Defining microbial safety in terms of a health outcome target of 10^{-6} DALYs pppy.
- Achieving safety through application of microbial performance targets based on the use of reference pathogens (8.1-log *Campylobacter*, 9.5-log enteric virus, 8-log *Cryptosporidium* reduction from untreated wastewater).

- Chemical guideline values based on those in the Australian Drinking Water Guidelines, augmented with an approach for setting interim guideline values or screening levels for pharmaceuticals, personal care products and other trace organics. The approach for setting interim guidelines is based on a hierarchy of existing toxicological information, tolerable doses for veterinary pharmaceuticals, lowest therapeutic doses for human pharmaceuticals and thresholds of toxicological concern. The main driver for including this approach was to provide a mechanism for responding to public concerns raised during debates about potable reuse. This was a major issue in the debate about the proposed Toowoomba scheme (see Appendix A4.3).

Appendix 4. Engagement case studies

A4.1 Singapore: NEWater, nothing new

In the city of Singapore, where up to 40% of the city's water demand of 1500 million litres per day (MLD) can be met by potable reuse (branded NEWater in Singapore), with a bigger and more ambitious plan to meet up to 55% of its water demand in the long term, water reuse has been an astounding success. Singapore's success with reused water has been well documented and much discussed in the global water fraternity, most notably in the area of securing public acceptance through a comprehensive and wide-ranging public communications programme targeting various groups of stakeholders.

NEWater, introduced in 2003, is primarily supplied to non-domestic sectors such as wafer fabrication plants, industrial estates and commercial buildings for industrial and air-cooling purposes. As NEWater is ultra-clean, it is ideal for processes that require highly purified water. During dry months, NEWater is also used to top up reservoirs.

To gain public acceptance of potable reuse Singapore set out to design an education and engagement process that would mitigate against the impacts of factors that inhibited trust and acceptance.

High on its agenda was engaging all possible groups of stakeholders early in the process with relevant information. This included political leaders, media, grassroots organizations, business associations and religious groups. To build public trust and confidence, exhibitions and roadshows were also held at the school and community level.

A panel of international and local water experts in the fields of engineering, biomedical sciences, chemistry and water technology provided independent expert testimony and addressed health, safety and quality issues. Their verdict: that NEWater was consistently of a safe, high quality, well within the drinking-water requirements of the World Health Organization and United States Environmental Protection Agency (USEPA).

Central to the entire public education campaign in Singapore was the establishment of the NEWater Visitor Centre, a state-of-the-art water museum that acts as a one-stop centre for anyone looking to understand how NEWater is produced and the part it plays in Singapore's water strategy.

The centre allows visitors to view the treatment process at the Bedok NEWater factory from a gallery and understand the science behind it through interactive displays, tours and workshops. The centre is open to community groups, individuals and foreign visitors. It has also become part of Singapore's National Education Programme, giving every student a chance to visit the NEWater Visitor Centre at least once during their time at school. Allowing the public greater access to the know-how of water reclamation has fostered trust and a sense of assurance.

Bottles of attractively packaged NEWater are available for public sampling, and this has helped the general population to judge for themselves the quality of NEWater.

Leading by example, the government demonstrated that the population's trust in them was well placed. The political leadership championed the move by publicly drinking NEWater. One of the earliest leaders was Mr Goh Chok Tong, the then Prime Minister of Singapore, who drank from a bottle of NEWater right after a tennis game. Other cabinet ministers and members of parliament followed suit, by toasting with NEWater at events held during National Day celebrations. The definitive moment that marked the population's support and confidence in NEWater and set the stage for its implementation in Singapore was the toasting of NEWater in a show of solidarity by some 60 000 Singaporeans during the 2002 National Day.

An independent survey by Forbes Research at the end of 2002 confirmed the success of the programme. NEWater had garnered a 98% acceptance rate, with 82% of respondents indicating that they would drink NEWater directly and another 16% would drink it mixed with reservoir water.

The presence of key opinion leaders to influence and champion the project is paramount, and in Singapore's case, instead of letting the media run with images that would turn the community off, one of the first things that the Public Utilities Board (PUB) did was to engage the media to gain support. Instead of the "toilet to tap" imagery, the result was fair and unbiased reporting ("Good as new", *Today*, 11 July 2002). Media reports also helped to frame NEWater in the right context of Singapore's water strategy ("Four big taps will keep water flowing", *The Straits Times*, 23 May 2002). Public endorsement by the country's leaders was a powerful and influential signal that served to garner public support, and this was duly conveyed by the media ("NEWater proves to be a smash hit with PM Goh", *The New Paper*, 1–2 August 2002).

Sustained public education and engagement with its stakeholders is an ongoing process, and the NEWater Visitor Centre continues to be the main vehicle for sustained public education on NEWater, with more than 1.3 million visitors to date. Key milestones, such as the opening of NEWater plants, and commemoration of the first and 5 millionth NEWater bottles, are celebrated to keep NEWater in the public eye and more importantly, maintain the public's confidence in NEWater. NEWater has won several awards for communication and education, including the "Water for Life" United Nations Water (UN-Water) Best Practices Award in 2014.

A4.2 Orange County Water District, California, United States of America: One programme, multiple benefits

The Orange County Water District (OCWD) initiated its first potable reuse system, Water Factory 21, in the 1970s and replaced it in 2008 by the Groundwater Replenishment System (see Case Study 2). The Groundwater Replenishment System, which is operated jointly by the OCWD and Orange County Sanitation District (OCSD) of Fountain Valley, California, currently produces 380 MLD of water – enough to meet the needs of nearly 850 000 people. Approximately two thirds of the advanced purified water is pumped to OCWD surface recharge facilities in Anaheim, California, and the remaining water is injected into a seawater barrier.

To ensure a comprehensive and sound assessment of potable reuse and aquifer recharge efforts, an independent advisory panel was established with experts from various fields, including toxicology, microbiology, hydrogeology, public health and environmental engineering. This panel provided public confidence that critical aspects of the projects have been independently and scientifically scrutinized.

Further, OCWD undertook a comprehensive public outreach and engagement strategy to bring about public acceptance of potable reuse which has been emulated by countries such as Australia, Singapore and many cities in the USA.

The aggressive outreach campaign to garner public acceptance for the Groundwater Replenishment System started a decade before the project came online in 2008. A public outreach consultant was hired, and initial research was conducted consisting of focus groups and telephone surveys within the OCSD and OCWD combined service areas. From this research, the following were identified: key issues (e.g. cost, health, safety, water reliability, suspicion of jargon, importance of RO purification) and target stakeholder audiences (e.g. business, environmental, political and other community leaders). The project's original name, Orange County Reclamation Project, was changed to the Groundwater Replenishment System because of research indicating that the former did not effectively communicate the project.

Outreach talking points also were developed as a result of focus groups and public polling. Initial outreach efforts focused on educating the political and community leadership of Orange County on the project and building a foundation of understanding and support. Subsequent phases broadened these efforts to reach the general public. From 1997 to 2007, more than 1200 face-to-face presentations about the science behind the Groundwater Replenishment System were given to local, state and federal policy-makers, business and civic leaders, health experts, environmental advocates, academia and the general public. These efforts were augmented by developing collateral materials (e.g. letters, newsletters, brochures, videos) and providing them to other water agencies, libraries, TV stations and special community events. In addition, a series of four public workshops were held across Orange County to receive citizen input prior to the decision in 2001 to proceed with the final engineering design.

Importantly, letters of support for the project were solicited and obtained from elected officials representing cities that would drink the water, as well as state and federal officials. Support was also obtained from the environmental, business, medical and minority communities.

Public tours have also been a critical element of the outreach programme. Both OCWD and OCSD provide free public tours of their facilities. OCWD receives hundreds of requests annually to provide tours of and briefings on the Groundwater Replenishment System for visitors from local colleges, water agencies, the surrounding community and international organizations.

Proactive outreach and education activities have continued throughout the design, construction, operations and initial expansion of the project. As a result of this proactive outreach campaign, the project has received no active public opposition. These outreach activities continue to remain a high priority for both OCSD and OCWD, with the ongoing goal of maintaining community support for the Groundwater Replenishment System by educating the next generation of local citizens and community leaders. OCWD's public outreach programme has won several awards.

A4.3 Toowoomba, Australia: No to water recycling

Faced with an ongoing water crisis, the city of Toowoomba, (approximately 100 km west of Brisbane, the capital city of Queensland, Australia) had plans to go ahead with a potable reuse proposal in 2006. At that time, the town, whose water supply came mostly from three major reservoirs, had seen dam levels drop to 20% of capacity. Water restrictions had also been in place since 2003.

To address the city's water challenges, the Toowoomba City Council announced the Water Futures initiative in July 2005, comprising a range of water solutions, key of which was the construction of an advanced water treatment plant to provide potable reuse water for the town. However, this was principally a policy document, and not a public communication document, although the Toowoomba City Council was planning to undertake a three-year community engagement programme as part of the proposal.

The Citizens Against Drinking Sewage public interest group reacted quickly to this proposal, coming out publicly to voice their opposition and provided arguments to support their position. They were well funded and politically motivated. They were the first to communicate and provide information about potable reuse to the public. In six months, 10 000 people had signed a petition against the proposal.

In March 2006, the Australian Government offered financial support subject to public support for the Water Futures project being demonstrated through a referendum held within months. The rationale for the referendum is not completely clear but in addition to public controversy, another factor was downstream agricultural interests that were concerned about the loss of water. Instead of the planned three-year community engagement programme, the Toowoomba City Council had to quickly condense the programme into a 10-week information campaign to educate the population on the project. They distributed a Water Futures booklet which contained explanations about the water cycle, the current level of water supply as well as possible water supply alternatives. However, by the time the council started engaging the public, the Citizens Against Drinking Sewage group had been communicating with Toowoomba residents for more than half a year, utilizing stigmatizing language and creating fear about public health. During this period, they continued to use public meetings, petitions and internet blogs to activate residents to vote "no" at the referendum while the council was hindered by the fact that the full education and engagement programme they had planned could not be funded until after the referendum.

The end result was telling. A majority 62% of residents voted against the proposed reused water scheme in the referendum held on 29 July 2006. The Water Futures project was abandoned. According to the media statements made by Citizens Against Drinking Sewage in the lead up to the referendum, it appeared that Toowoomba did not want to be the first, or the only, location in Australia to drink reused water. Other compelling factors such as political interests, clashes of strong personalities on both sides of the debate, mistrust surrounding the public information campaign, timing and the absence of national guidelines for potable reuse all played a part in influencing public opinion.

Of particular note, the solution to the dire water shortage in the greater South East Queensland region, including Toowoomba, was the development of a water grid connecting a range of supplies, including the Western Corridor potable reuse scheme in Brisbane which was designed to supply highly treated wastewater to the major water supply dam, Wivenhoe. A pipe was constructed linking Toowoomba to the grid. While the advanced treatment trains were installed political opposition in Queensland also had an impact on this project. Ultimately heavy rains leading to major floods have meant that the Western Corridor scheme has been held in reserve and not used (as of 2016).

A4.4 San Diego, California, United States of America: Where persistence paid off

Although technically neighbours in populous Southern California, San Diego and Orange County have tried to implement potable reuse to varying degrees of success. While Orange County is an exemplary model of a successful potable reuse programme, the potable reuse project in the city of San Diego was dogged with negative associations and "toilet to tap" phrases during its first attempt to propose a reuse project.

Heavily dependent on imported water for 80–90% of its water supply, the city of San Diego began considering potable reuse in 1984, with a full-scale project approved in 1994. The drivers at that time were drought conditions, as well as the fact that the Point Loma WWTP was given until 2015 to meet USEPA discharge standards.

The public communications campaign was controversial. Unlike Singapore, there was no consistent political support for the proposal. There was public mistrust over the project, stemming mainly from the inadequacy of answers in addressing questions on health and safety issues. The media labelled the project as "toilet to tap", evoking negative imagery to amplify public concerns. Although a small group of opinion leaders were involved, the general community had no understanding that the imported water coming into San Diego was already reused. There was also a perception of bias. The proposed project was going to use treated wastewater from an affluent area of San Diego as a source (after advanced treatment) of drinking-water to be provided to a low-income area. Hence, in addition to "toilet to tap", San Diego was plagued by the mantra of "the effluent of the affluent", which created additional outrage that the reuse was unfairly being used in only one area. In the face of such public resistance, the project was eventually aborted.

By 2004, potable reuse was back on the agenda. With increasing weather variability leading to prolonged drought conditions, San Diego began looking at potable reuse in 2004 to evaluate all options for increasing its water supply. The city council commissioned a water reuse study to comprehensively research all opportunities for reusing water, and a second study was conducted in 2009. Ultimately, one of the key arguments that helped to shift public opinion was that partially treated wastewater discharges to the ocean would be significantly reduced, which encouraged support from environmental groups.

Around that time, some industries were threatening to move away from San Diego because of the water shortage. Political support increased to a great degree because of the appreciation that ocean wastewater discharges would be significantly reduced as a result of the wastewater recycling. The city therefore conducted a demonstration project from 2009 to 2013 to explore the feasibility of implementing the same water purification process used successfully by OCWD, although San Diego was planning to discharge the highly treated water into an uncovered reservoir followed by passage through a drinking-water treatment plant. The compiled data culminated in the Pure Water San Diego programme, a 20-year potable reuse project that would see up to 57 MLD of reused water by 2023. The long-term hope is that output will be increased to 315 MLD of purified water by 2035, accounting for over one third of the city's total supply.

Learning from its past experience, the city is also embarking on an active public communications programme to reach out to all its stakeholders with materials and information about the project readily available. Tours to the reuse facility are also facilitated.

Appendix 5. Potable reuse case studies

Scheme	Type	Environmental buffer (IPR only)	Start date	Treatment process (after secondary wastewater treatment)
CS1 Windhoek, Namibia, Goreangab reclamation plant				
Old Goreangab plant, Windhoek, Namibia	DPR	—	1969–2002 (replaced)	Algae flotation, chemical clarification, media filtration, granular activated carbon, chlorination
New Goreangab plant, Windhoek, Namibia	DPR	—	2002	Ozonation, dissolved air flotation, rapid sand filtration, ozonation, biological activated carbon, granular activated carbon, ultrafiltration, chlorination
CS2 Groundwater Replenishment System in Orange County, California, United States of America				
Water Factory 21, Orange County, California, USA (replaced, see below)	IPR	Groundwater	1976 (replaced)	Lime clarification, media filtration, granular activated carbon, chlorination, reverse osmosis added 1977, advanced oxidation process (ultraviolet/hydrogen peroxide) added 2001
Groundwater Replenishment System, Orange County, California, USA	IPR	Groundwater	2007	Chlorination, microfiltration, reverse osmosis, advanced oxidation process (ultraviolet/hydrogen peroxide)
CS3 Upper Occoquan Service Authority potable reuse project in Virginia, United States of America				
Upper Occoquan Service Authority, Fairfax County, Virginia, USA	IPR	Surface water	1978	Lime clarification, media filtration, granular activated carbon, chlorination, chloramination
CS4 Water reuse in Singapore – NEWater				
NEWater, Singapore	IPR	Surface water	2003	Ultrafiltration, reverse osmosis, ultraviolet
CS5 Perth, Australia, groundwater replenishment				
Beenyup groundwater replenishment scheme, Perth, Australia	IPR	Groundwater	2016	Ultrafiltration, reverse osmosis, ultraviolet
CS6 Direct potable water reuse in Texas, United States of America				
Big Spring, Texas, USA	DPR	—	2013	Microfiltration, reverse osmosis, advanced oxidation process (ultraviolet/hydrogen peroxide), blending, media filtration, chlorination
CS7 Water reuse in South Africa: The eMalahleni water reclamation plant				
eMalahleni Municipality, South Africa	DPR (mine waste)	—	2007	Oxidation/neutralization, clarification, ultrafiltration, reverse osmosis, chlorination

CS1 Windhoek, Namibia, Goreangab reclamation plant

CS1.1 Overview and background

When the City of Windhoek decided in 1968 to implement DPR it was a bold step, as at the time, no standards or guidelines for drinking-water from recycled wastewater were in existence. Windhoek was the first city in the world to introduce planned potable reuse. It was, however, not a step taken lightly, but was the outcome of years of research and piloting, starting with pilot plants at the Gammams WWTP (Gammams) in Windhoek and the so-called Stander plant at Daspoort in Pretoria.

One of the pioneers on the Windhoek plant, the late Dr Lukas van Vuuren, coined the phrase that "Water should be judged by its quality, not by its history". However, literature of the time does not seem to provide any quantitative quality targets that the treated wastewater was to meet, but rather suggested that specific process steps that had the ability to remove specific constituents of concern be designed and incorporated into the treatment process.

As shown in Table CS1.1, the plant evolved over 40 years of development and 30 years of full-scale operation, with improvements introduced through six stages, culminating in replacement of the original (old) Goreangab reclamation plant with the new Goreangab plant in September 2001. The treatment train included in the new plant is shown in Figure CS1.1

CS1.1.1 Drivers for potable reuse in Windhoek

Windhoek is situated on a watershed at the upper end of the Upper Swakop River basin. The first recorded formal settlement in Windhoek occurred towards the end of 1840 at the hot springs in what is known today as Klein Windhoek. Ironically, the abundance of water was the reason why Windhoek was chosen as a place to settle. By 1911 the springs and hand dug wells had become inadequate and the first state owned water scheme was developed by drilling a borehole. A second borehole was drilled in 1913 and until 1959 groundwater remained the only source of water supply.

Early in the 1950s, it became apparent that within 10 years, serious water problems would arise in Windhoek and that additional water sources would have to be found. There are no perennial rivers within 750 km of the city. Suitable dam sites were far from the city and would have resulted in very high pumping costs. The city council approached the South African National Institute for Water Research (NIWR) for advice. The Director of NIWR (Dr Stander) considered that potable reuse was a readymade solution to the problem (*Scientiae*, 1969).

The water crisis of 1957, once again showed the vulnerability of the city when groundwater resources were reported to be used at a level 57% above safe yield. Water levels dropped by up to 52 m in four months. In a submission to the South West Africa Administration Water Affairs Branch it was stated that the reuse of suitably treated wastewater for certain special purposes, such as the power station and cemetery, would appear to be a measure likely to yield positive results by September 1958.

The 95th percentile safe yield of the three-dam system serving Windhoek and the central areas of Namibia, is 20 gigalitres (GL) per annum of which 17 GL is available to Windhoek. In 2015, the demand of the city was 26 GL per annum. Without the contribution of reuse and groundwater, demand could not be met. Direct potable reuse is an indispensable source of water for Windhoek (Figure CS1.2).

To meet increasing demand for reuse water, it is planned to expand the Gammams plant from 28 MLD to 55 MLD using a two-train operation (a 20 MLD nutrient removal-activated sludge process train and a 35 MLD MBR train). The treated wastewater from the ASP plant will remain the feedwater for the new plant, where physical constraints on hydraulic capacity will not allow significant expansion. The City of Windhoek has called for consulting services for establishing an advanced treatment drinking-water plant at Gammams to follow the new MBR plant.

Table CS1.1 Summary of the history and development of the Goreangab reclamation system in Windhoek, Namibia, 1962–2016

Upgrade	Wastewater treatment (#1)	Maturation ponds (retention)
1962–1979	PI: Biological filters	10–14 days
1979–1994	PII: Activated sludge nutrient removal	6–10 days
1994–2016	PIII: Activated sludge nutrient removal	3–6 days

#1 PI Primary settling – biofilters – secondary settling – maturation ponds (14 days)
#1 PII Primary settling – five-stage bardenpho nutrient removal activated sludge – secondary settling – maturation ponds (10 days)
#1 PIII Primary settling – University of Cape Town or modified Johannesburg nutrient removal activated sludge – secondary settling – maturation ponds (6 days)

Upgrade	Windhoek DPR plant (#2)	Capacity
1968–1976	Goreangab Mark I	4.8 MLD
1976–1980	Goreangab Mark II	4.8 MLD
1980–1986	Goreangab Mark III	4.8 MLD
1986–1994	Goreangab Mark IV	7.2 MLD
1994–2001	Goreangab Mark V	14.4 MLD
2002–2016	Goreangab Mark VI	21 MLD

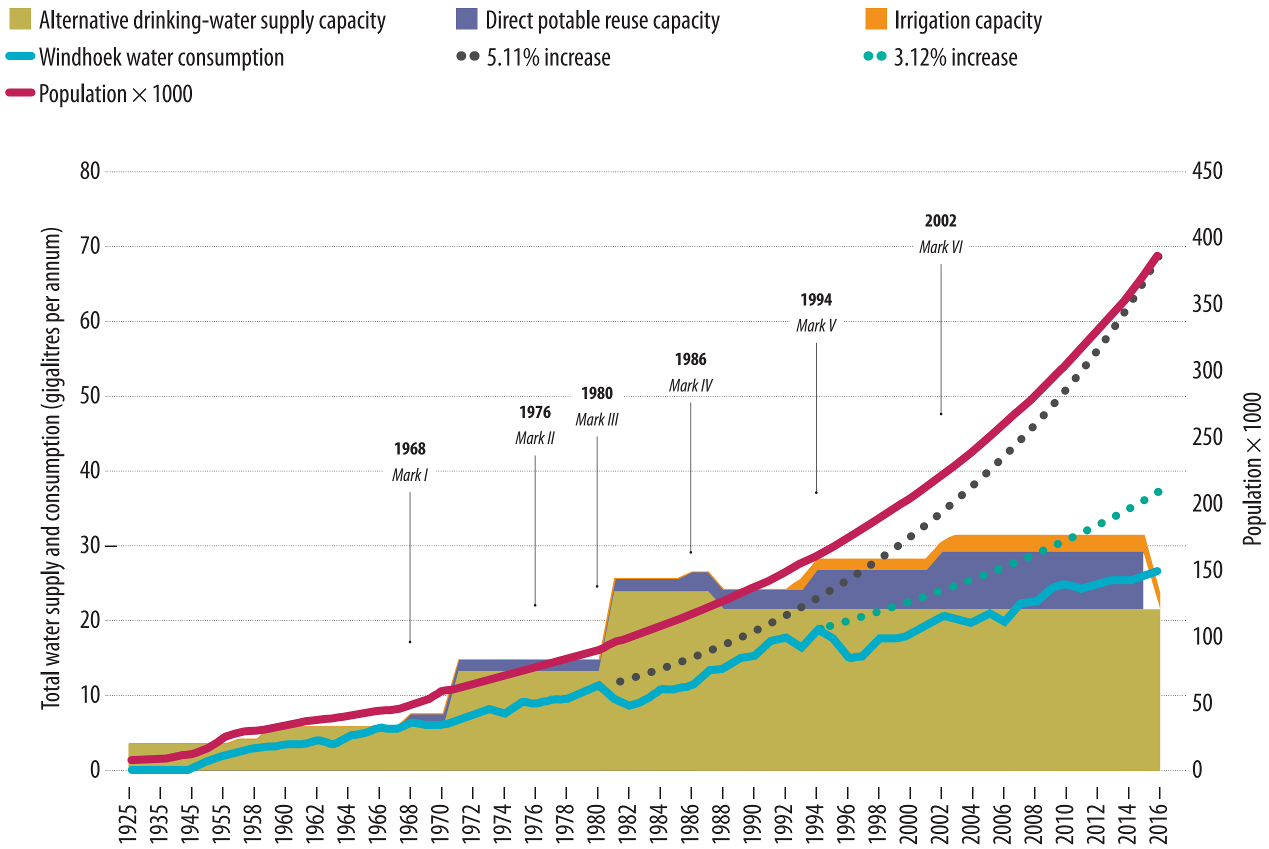
#2 Mark I (Carbon dioxide), (alum), algae flotation, foam fractionation, (alum + lime), (breakpoint chlorination), settling, rapid sand filtration, activated carbon, (chlorine), blending
#2 Mark II (Lime), settling, ammonia stripping, (carbon dioxide), (chlorine), (alum + lime), settling, (carbon dioxide), rapid sand filtration, (breakpoint chlorination), activated carbon, (chlorine), blending
#2 Mark III (Chlorine), (alum + lime), settling, (breakpoint chlorination), (alum + lime), settling, rapid sand filtration, (chlorine), activated carbon, (chlorine), blending
#2 Mark IV (Alum + lime), dissolved air flotation, (chlorine), (alum + lime), settling, rapid sand filtration, (breakpoint chlorination), activated carbon, (chlorine), blending
#2 Mark Va (Ferric), dissolved air flotation, rapid sand filtration, activated carbon, (breakpoint chlorination), (stabilization: lime), (chlorine), blending
#2 Mark Vb (Ferric), dissolved air flotation, rapid sand filtration with filter to waste – rapid sand with filter to waste + granular activated carbon, activated carbon, (breakpoint chlorination), (stabilization: sodium hydroxide), (chlorine), blending

Note: The bracketed components, except for those indicating maturation pond detention times, are all chemical dosing steps. P=phase.
Source: City of Windhoek, Namibia.

Figure CS1.1 New Goreangab water reclamation plant treatment train

Source: City of Windhoek, Namibia.

Figure CS1.2 Windhoek water consumption compared with the available natural water sources and reuse sources



Note: The different plant upgrades are also indicated as well as the population served.
Source: City of Windhoek, Namibia.

CS1.1.2 History and current status

During the mid-1960s, following favourable results from the Gammams pilot plant, the Municipality of Windhoek Council took a decision to implement potable reuse. Direct potable reuse was officially born at the Goreangab water reclamation plant on 21 January 1969 when the plant, with an initial capacity of 3.287 MLD (1.2 GL per annum) was inaugurated. The plant was owned by the Municipality of Windhoek who, with government funding for infrastructure, was solely responsible for water supply from three sources: groundwater, surface water from the Goreangab Dam, and potable reuse from the Goreangab plant.

During the period 1969 to 1982, three surface reservoirs were added by the government. These reservoirs, with a total capacity of 155 GL, were between 70 and 200 km from Windhoek and, being on ephemeral rivers, had a 95th percentile assured yield of only 20 GL. Semi-purified irrigation and water demand management were introduced between 1993/94. During the drought of 1996 the city council, resolved to reuse every available cubic metre of wastewater.

The Goreangab plant was upgraded five times over its lifetime and in 2001 a new plant was put into operation with an initial capacity of 21 MLD.

CS1.1.3 Ownership

The City of Windhoek owns the plant. It is contracted out to Windhoek Goreangab Operating Company, an international private partnership company. The 20-year contract is managed through a private management agreement.

CS1.2 Development of the potable reuse scheme

CS1.2.1 Sources of water and source control

During the early 1960s, when potable reuse was contemplated, a decision was taken by the then Municipality of Windhoek, to separate industrial wastewater from domestic wastewater. To enforce this change on existing industry would have been impractical. A new industrial township was therefore established to the north of the city and outside of the existing Gammams drainage area. The Goreangab plant uses the secondary wastewater from the Gammams WWTP as source for reuse.

A new industrial wastewater plant was established and as far as possible all industry with industrial wastewater, was accommodated in the northern industrial area. Even today, there are still a few exceptions that drain to the Gammams plant, but discharges from these industries are strictly controlled and industrial wastewater charges, inclusive of penalties, are used to minimize the effect of these on the reuse process. Source control by way of automatic composite sampling at individual discharge points, is used to ensure compliance.

CS1.2.2 Piloting

In the early 1960s, a pilot scale plant was installed at the Gammams WWTP, (Clayton, 2005). This pilot study was undertaken jointly between the City Engineer's Department and the NIWR.

At the time the building of the Windhoek reclamation plant was approved, a similar full-scale research unit with a capacity of 4.8 MLD was built at Daspoort, Pretoria, where all future reuse research would be conducted by the NIWR. Here, extensive research was conducted to improve the existing treatment process. The biological nutrient removal-activated sludge process was compared with biological trickling filters. High lime treatment and ammonia stripping, breakpoint chlorination and activated carbon adsorption were all piloted at Daspoort. Known toxic compounds and organic micro-pollutants were determined and their removal was established during spiking exercises. Biological surveillance assays and bioassays were simultaneously conducted to detect any acute or sub-lethal activity. Concentrations of these compounds tested, were removed by more than 99.9% of their original concentration, to levels below detection limits. No biological activity, bacteria, virus or coliphages could be detected in the final water. Comparing the treated wastewater quality with conventional drinking-water sources from surface and boreholes, it was concluded that the treated wastewater was of a better quality. These promising results led to the upgrade and extension of the Mark I plant. Research continued and many different advanced treatment processes were tested in the following years. Many of the research efforts received international acclaim.

CS1.2.3 Regulatory context

As discussed in Appendix A3.1, both the old and new plants were introduced in the absence of water quality standards for potable reuse. In the absence of enforceable guidelines and standards, the City of Windhoek accepted self-regulation by adopting standards from international drinking-water standards for the design of the new plant.

CS1.3 Control measures

CS1.3.1 Control strategy

Industrial pollution, in particular the practice of releasing synthetic chemical compounds to receiving streams, represents a potential health hazard. Therefore, it was of paramount importance that these compounds had either to be totally removed from drinking-water or the concentrations reduced to such a level that the risk of exposure was as low as possible.

When the Mark I plant was established in 1969, it was based on a clearly defined policy of total reclamation and entailed four integrated lines of defence. These lines of defence included:

- Wastewater catchment quality control based on the diversion of industrial discharges containing potentially harmful chemical compounds from the domestic wastewater collection system.
- Efficient reclamation technology backed by vigilant control. Aspects of concern were the efficiency of such a plant to remove pathogenic microorganisms, toxic metals and organic compounds which may be mutagenic, teratogenic or have other detrimental effects.

- Vigilant surveillance of the final water produced, which included a comprehensive determination of the microbial and chemical quality of the water as well as the use of early warning systems, based on biological sensors such as fish.
- Continuous measurement of the chlorine content of the water and those chemical constituents that might be measured on a continuous basis such as DOC and the UV absorption of the water.

From the early 1970s, microbiological and chemical quality control studies indicated that the product of the reclamation plant was of good quality and conformed to generally accepted drinking-water criteria. As shown in Table CS1.1, the plant has been upgraded over the years, increasing the capacity of the plant to remove chemical and microbial hazards.

CS1.3.2 Identification and monitoring of control measures

Control measures focused on the removal of synthetic detergents and organic pollutants by wastewater treatment and removal of microbial pathogens with advanced drinking-water treatment unit processes as well as removal of DOC, total halogenated compounds, metals and aesthetic parameters. Each treatment process had to be operated within defined operating conditions or parameters to ensure maximum removal of contaminants. Operational analyses ensured that the treatment objectives were reached. Laboratory analyses were conducted to verify that the water had been treated adequately. Initially, at least four different institutions were involved in monitoring. Two institutions had the mandate to conduct unscheduled sampling at least once a month and to analyse mainly for bacteria, virus and chemical substances, whereas another two were responsible for the scheduled routine monitoring of the full spectrum of water quality parameters. In order to deal with changes in the raw water, or processes that did not perform adequately, process steps were either improved or replaced with more appropriate treatment technologies.

CS1.3.3 Verification and epidemiological evidence

In 1976, when the Mark II plant upgrade was commissioned, it was recommended that a general standard for the quality of the maturation pond effluent should be established. The safety barriers of the Mark I plant had been effective and any additional safety barriers, which would increase safety, could be implemented immediately. Final water had to comply with the South African Bureau of Standards drinking-water specification (No. 241-1971), which was slightly refined for DPR. Standardization of methods for analysis of chemicals, bacteria and viruses between all laboratories was made a priority and inter-laboratory studies were introduced. Further research was undertaken to define analytical parameters more accurately, for example free chlorine, total chlorine, chlorine demand, and to develop standardized methods for these. High lime treatment with ammonia stripping and a further chlorination barrier were introduced.

It was recognized that epidemiologic studies were an imperative requirement (Isaäcson et al, 1987). Therefore, an epidemiological study was commissioned and the following tests were also carried out:

- continuous fish bio monitoring
- mutagenicity testing
- tissue culture tests for hazardous chemicals
- mammalian tests for carcinogenicity.

Bioassays of public water were to consider not only lethality but also sub-lethal effects important to the well-being of any species. Online fish bio monitoring was introduced as a quick, simple and comparatively inexpensive method for assessing sudden changes in water quality. For long-term exposure tests, the following were considered:

- change in scope for activity and general health
- serologic changes
- pathologic changes.

Studies undertaken by the South African Institute for Medical Research from 1974 to 1983 first dealt with the microbiological surveillance of the treated wastewater. Based on more than 4000 samples tested it was concluded that treated wastewater conformed to generally accepted quality standards laid down for domestic water supplies and was fit for human consumption. From a virological point of view, the source of treated wastewater, i.e. human wastewater, was shown to be consistently contaminated with potentially pathogenic viruses, in contrast to untreated conventional surface water sources. The water was regularly tested at different stages in the reclamation process. Viruses became progressively fewer in number and were consistently absent from the final stages in the process. The studies were expanded in 1976 and embraced both potential short-term (mainly infectious) and long-term (mainly non-infectious chronic) effects. The authors of the report further concluded that, within the limits of the epidemiological studies done, no adverse effects on health attributable to the consumption of treated wastewater could be demonstrated (Isaacson & Sayed, 1988). This conclusion was further supported by a study on the health effects of the Montebello Forebay IPR scheme in Los Angeles County, California (Nellor et al, 1984). This study concluded that no viruses could be detected in chlorinated treated wastewater. An evaluation of health and vital statistics over a period of 12 years showed that residents of the area that received potable reuse water experienced no increased rates of infectious diseases, congenital malformations, infant and neonatal mortality, low birth weight, cancer incidence or deaths due to heart disease, stroke, cancers of the stomach, rectum, bladder or colon, or all cancers combined, when compared with residents of two control areas that did not receive potable reuse water.

CS1.3.4 Environmental buffer

Windhoek is a DPR scheme and does not have an environmental buffer. The treated water from the WWTP flows through several maturation ponds before entering the reclamation plant. The volume of these ponds had remained constant, meaning that the retention time decreased from 14 days for the Mark I plant, to under three days for the new plant, as flows increased. This loss of security was compensated by technology improvements, online monitoring, automation of plant processes and faster response times to analysis. Currently, the final treated wastewater is retained in a reservoir to facilitate the maintaining of the desired blending ratio with surface water at a pump station, from where the blended water is distributed to several reservoirs in the distribution network. The retention varies from four to eight hours.

In the absence of an environmental buffer, the private management agreement was structured to ensure that the operator was always incentivized to achieve the prescribed water quality. Payments to the operator are calculated in terms of the water meeting intermediate standards after every process step as well as final water standards. Failure to meet target values attracts financial penalties, while failure to meet maximum or absolute values, means putting the plant to recycle mode with zero output, until the product water complies with specifications. If the operator is unable to meet the absolute values and zero water is delivered, payment is suspended. It is mandatory for the operator to have all barriers in operation at all times.

CS1.4 Water quality monitoring

CS1.4.1 Operational and verification

Research was conducted to test the reliability of the processes under varying conditions. Each treatment process had to be operated within defined operating conditions or parameters to ensure maximum removal of contaminants. Operational analyses ensured that the treatment objectives were reached. Laboratory analyses were conducted to verify that the water had been treated adequately. As stated, at least four different institutions were involved in monitoring. In the early days, two institutions had a mandate to undertake surprise sampling at least once a month and to analyse mainly for bacteria, viruses and chemical substances, whereas two were responsible for conducting scheduled routine monitoring of the full spectrum of water quality parameters.

During the period 1980–1990 the Mark III and Mark IV plant upgrades were commissioned, which also extended the production of treated wastewater. An online automatic DOC analyser and UV254 monitor was introduced by the NIWR to monitor the product from the GAC columns.

The primary objective of research on the microbiological water quality (Grabow, 1984; 1990), was to establish the safety of the treated wastewater and to develop methods for reliable routine quality surveillance by means of tests which could be carried out at high frequency and relatively low cost in laboratories with limited expertise and facilities. It included the selection of practical and reliable indicator organisms that had to be present whenever pathogens are present, specific for faecal or wastewater pollution, at least as resistant as pathogens to water treatment and disinfection processes, preferably non-pathogenic, and detectable by simple, rapid and inexpensive methods.

At the time the report of this research was written, 13 000 L of final treated wastewater had been filtered for detection of viruses. Sample volumes were 10 L at the early stages of the research and later 100 L. No viruses had been detected, implying that the treated wastewater was well within the most stringent virological quality limits recommended for direct reclaimed drinking-water in the existing international literature.

Clostridium perfringens was found to be a useful indicator, being highly specific for faecal pollution and detection by relatively practical methods within 24 hours.

Assessment of chlorination indicated that viruses and coliphages tended to be more resistant to combined chlorine than bacteria, while bacteria tended to be more resistant to free chlorine residuals than viruses and coliphages. This implied that bacteria such as coliforms were reliable indicators of the inactivation of viruses by free chlorine residuals as applied in the reclamation plants. It was concluded that the combined effect of the various process units in the multiple-barrier reclamation system conformed to the most stringent requirements for microbiological safety of directly reclaimed drinking-water, including the capability of reducing viral counts by 12 log units.

The following criteria were recommended for direct potable drinking-water: absence of viruses from 10 L, heterotrophic plate count ≤100 colony-forming units (CFU)/ml, and absence of total coliforms, acid-fast bacteria, *P. aeruginosa* and coliphages from 100 ml samples after at least two process units in the treatment train. The bacterial and coliphage tests had the advantage that, if required for any reason, their sensitivity could easily be increased by testing larger volumes of water. In view of these findings, the following guidelines were recommended for routine water quality surveillance of an established multiple-barrier treatment system of proven efficiency such as the Windhoek reclamation plant:

- In 95% of samples collected daily after at least two treatment stages, a heterotrophic plate count of ≤100/ml, total coliforms and coliphages should be absent from 100 ml samples.
- At least one disinfection process should consistently conform to the following or equivalent specification: a free chlorine residual of 1–2 mg/L for retention time of one to two hours at a pH of less than 8.0 and a turbidity of less than 1.0 NTU.

It was established that, if drinking-water was disinfected with chlorine with a concentration of 1 mg/L free chlorine residual at a pH <8 and turbidity <1.0 NTU with a one-hour contact time, the water complied with all microbiological criteria. The major weakness of the disinfection process was that under certain conditions, organohalogen by-products were formed. The reduction of these organohalogen by-products became a major research focus in the following years.

Ultimately, final water quality guidelines were defined for the Mark VI plant (Table CS1.2). This table only contains the main operational test parameters. Other parameters of concern, such as heavy metals, aromatics or pesticides, were specified according to the Rand Water (1994) or USEPA (1996) guidelines.

Table CS1.2 Guideline limits for the Mark VI plant

	Units	Target	Maximum
Physical and organoleptic			
Calcium carbonate precipitation potential	g/L	4	0–8
Chemical oxygen demand	mg/L	10	15
Colour	mg/L Pt	8	10
Dissolved organic carbon	mg/L	3	5
Total dissolved solids	mg/L	≤1000	≤1200
Turbidity	NTU	0.1	0.2
UV254	abs/m	5.0	6.0

Table CS1.2 (continued)

	Units	Target	Maximum
Macro elements			
Aluminium	mg/L	N/A	0.15
Ammonia	mg/L	N/A	0.10
Chloride	mg/L	Not removed	250
Iron	mg/L	0.05	0.1
Manganese	mg/L	0.0025	0.005
Nitrate and nitrite	mg/L	Not removed	10
Nitrite	mg/L	Not removed	0.2
Sulfate	mg/L	Not removed	200
Microbiological indicators			
Heterotrophic plate count	per 1 ml	80	100
Total coliforms	per 100 ml	N/A	0
Faecal coliforms	per 100 ml	N/A	0
Escherichia coli	per 100 ml	N/A	0
Coliphages	per 100 ml	N/A	0
Enteric viruses	CPE[a] per 10 L	N/A	≤0 or 4-log reduction
Faecal streptococci	per 100 ml	N/A	0
Clostridium spores	per 100 ml	N/A	0
Clostridium viable cells	per 100 ml	N/A	0
Disinfection by-products			
Total trihalomethanes	µg/L	20	40
Biological			
Chlorophyll a	µg/L	N/A	1
Giardia	per 100 L	≤0 or 6-log reduction	≤0 or 5-log reduction
Cryptosporidium	per 100 L	≤0 or 6-log reduction	≤0 or 5-log reduction

[a]CPE = cytopathic effect.
Note: Other parameters will be adhered to as per Rand Water (1994) or USEPA (1996) guidelines.

CS1.5 Incident management

CS1.5.1 Protocols

The private management agreement with the Windhoek Goreangab Operating Company, specifies the attainment and maintenance of ISO 9001 certification and hazard analysis and critical control points protocols.

The operations protocol supported by ISO and hazard analysis and critical control points protocols, prescribes the recording of all incidents. A fully described system of responses is defined and maintained by the operator. The company is audited annually by ISO to ensure compliance. A monthly management report is given to the City of Windhoek to evaluate the operations and financial claims. A risk assessment carried out over the full plant to evaluate the adequacy of the different barriers and critical control points (CCPs) for the removal bacteria, viruses and protozoa resulted in recommendations for an upgrade. During the annual research meetings, attended by senior researchers and design experts from the city and the operator parent companies, monitoring reports and research reports are discussed and recommendations made for plant upgrades or improvements.

CS1.5.2 Experiences

In the early 1990s, a virus breakthrough was recorded. Between 1994 and 1999, breakthrough of *Giardia* and *Cryptosporidium* cysts and oocysts were recorded. In both instances, the acceptable guideline but not the maximum allowable limit was breached. Changes in the treatment and operations were instituted after the incidents.

Two main problems that have manifested themselves in Windhoek, are rising TDS and bromate formation. It has long been accepted that some form of desalination would have to be pursued in order to deal with TDS, and if RO were introduced, it would also resolve the bromate problem. However, Windhoek is in an inland area without any flowing rivers, access to the ocean or major saline aquifers to dispose of brine.

CS1.6 Public outreach

CS1.6.1 Stakeholder engagement

Piloting of the reclamation process ran from the early 1960s until the Goreangab plant was inaugurated in 1969. Gauging by newspaper reports at the time, the public of Windhoek and especially school groups, were encouraged to visit the pilot plant to witness the process. At the time, a structured programme of public engagement was not followed, (at least not reported on), but the public was represented by the national health and medical fraternity, as is evident from publications.

A liaison committee, formed around 1962, coordinated research, implementation and operation of the first reclamation plant. A steering committee was formed in 1973, taking over the mandate of the liaison committee. The committees comprised engineers, health officials from state and local government, scientists, and researchers from the Windhoek Municipality, NIWR, the Water Research Commission, Ministry of Health, Ministry of Water Affairs, the South African Institute for Medical Research and South African universities.

The monthly publication *Scientiae* (Council for Scientific and Industrial Research, 1967) reported that: "Extensive tests have proven that the drinking-water produced by the pilot plant is completely safe for human consumption. For instance, the Poliomelitus Research Foundation has affirmed the efficiency of the process for removing pathogenic organisms from the treated wastewater. Under the supervision of some of its research staff, cultures of polio virus and an entero-virus were introduced into the water flowing through the pilot plant at levels considerably higher than those anticipated in practice. Examination of the purified water revealed that these viruses had been completely eliminated."

Free information sharing of this type in the public domain has always been regarded as important and the process has been conducted in a transparent and open way.

In subsequent years, reclamation in Windhoek had always been highly publicized in scientific journals and on national and international platforms. The City of Windhoek, through its own publications and all available media platforms, has always given high levels of visibility to the fact that Windhoek has been and remains a pioneer in DPR. In recognition of these efforts, the 9th IWA International Water Reuse Conference (October 2013) was awarded to the City of Windhoek. Over the years, numerous local and overseas students have participated in research work and scholars and students have been encouraged during vacations to participate in projects to familiarize themselves with the operation and quality control of the reuse scheme. As part of the private management agreement, the private operator has to engage in social projects and an annual budget is allocated for this initiative.

The reclamation plant has been and remains a flagship project of the city and country; local and international visitors and experts, governmental and foreign mission personnel are regular visitors. Local and international students engage in scientific and social research work on potable reuse. The Goreangab plant is on the fixed list of venues for Ministry of Education programmes for schools and tertiary education institutions in which scholars are encouraged to engage in programmes on water and reclamation. There is specific budgetary provision that caters for the support of student and scholar projects. The media are invited on regular occasions to publish about the plant. A programme is in place to investigate all public complaints free of charge. Formal feedback is given in every case. Such complaints are evaluated and are part of the annual improvement programme.

CS1.7 Governance

During the first part of the planning, piloting, design and operation the City of Windhoek, Council for Scientific and Industrial Research, Department of Water Affairs, Department of Health and Medical Research and universities were partners. Engineers and scientists visited American institutions involved in potable reuse. The local regional health officer had the authority to undertake surprise inspections and sampling and close the plant down if not complying with the guidelines. A steering committee met once or twice annually to review all records and monitoring programmes and to recommend changes.

After Independence from South Africa in 1990, the Department of Water Affairs was restructured, where water supply was placed in a state owned enterprise, NamWater. The Department of Water Affairs retained the regulatory function. As formal support from South African governmental institutions was discontinued, the City of Windhoek took over all responsibility for the reclamation process. In order to maintain objectivity, local and international specialists in various disciplines were invited to steering committee meetings that were held every five years. They also assisted with the design of the new plant. The National Chief Forensic Officer was part of the steering committee and represented the public. Verification monitoring had to be done by at least three independent laboratories that did routine and specialist analysis, of which one always had to be accredited.

In terms of the private management agreement, the private operator is in full operational control of the plant, including process and quality management. The City of Windhoek buys the treated water from the operator at a tariff that is controlled through an open book system with a pre-determined fixed profit margin. The tariffs paid are directly linked to meeting all intermediate and final water quality requirements.

The operator takes all quality control samples, which are analysed by the city's laboratory and a protocol exists to deal with quality disputes. The plant is also installed with a high number of online monitoring instrumentation and all operational and quality information is stored on SCADA, which is open for access by the city.

CS1.8 Conclusions

The City of Windhoek has practised DPR for 45 years and it is fully accepted by consumers. The lack of natural water resources was the driver for DPR and experience has shown that it has been successful. There has been no need to reconsider the wisdom of the decision to regard treated wastewater as a safe and reliable source for the production of drinking-water. In the event of the proposed future implementation of advanced treatment at the Gammams WWTP, the city will have to reconsider the current limit of 35% treated wastewater in the blend. New guidelines being developed in South Africa might influence the proposed future process, but in Windhoek, DPR has been in the past and will remain in future, an integral and indispensable part of water supply.

Further reading

Barnard JL (1976). A review of the biological phosphorus removal in activated sludge process. Water SA. 2(3).

Brand JG (1957). On the water position in Windhoek during November 1957 and the expected consumption trend for the future. Memorandum of the town engineer, Windhoek, dated 16 November 1957 and submitted to the Secretary of South West Africa on 18 November 1957.

Menge J, Du Pisani P, van der Merwe B (2007). Water quality control in a third world country: Challenges to ensure good quality reclaimed water in Windhoek, Namibia. Proceedings at the 6th International Water Association Specialist Conference on Wastewater Reclamation and Reuse for Sustainability – Guiding the growth of future reuse. October 2007. Antwerp, Belgium.

Van der Merwe B, Du Pisani PL, Menge JG, König E (2005). Water reuse in Windhoek: 37 years and still the only case of direct water reuse for human consumption.

Van Vuuren LRJ, Meiring PGJ, Henzen MR, Kolbe FF (1965). The flotation of algae in water reclamation. International Journal Air and Water Pollution. 9:823–832.

Van Vuuren LRJ, Offringa G, Williams PG (1985). Development and application of DAF technology in South Africa. In: The Institute of Water Pollution Control Year Book and Buyers Guide, 1985–1986. 75–89.

World Construction (1969). Direct cycle water reuse in South Africa. World Construction. 22(9).

CS2 Groundwater Replenishment System in Orange County, California, United States of America

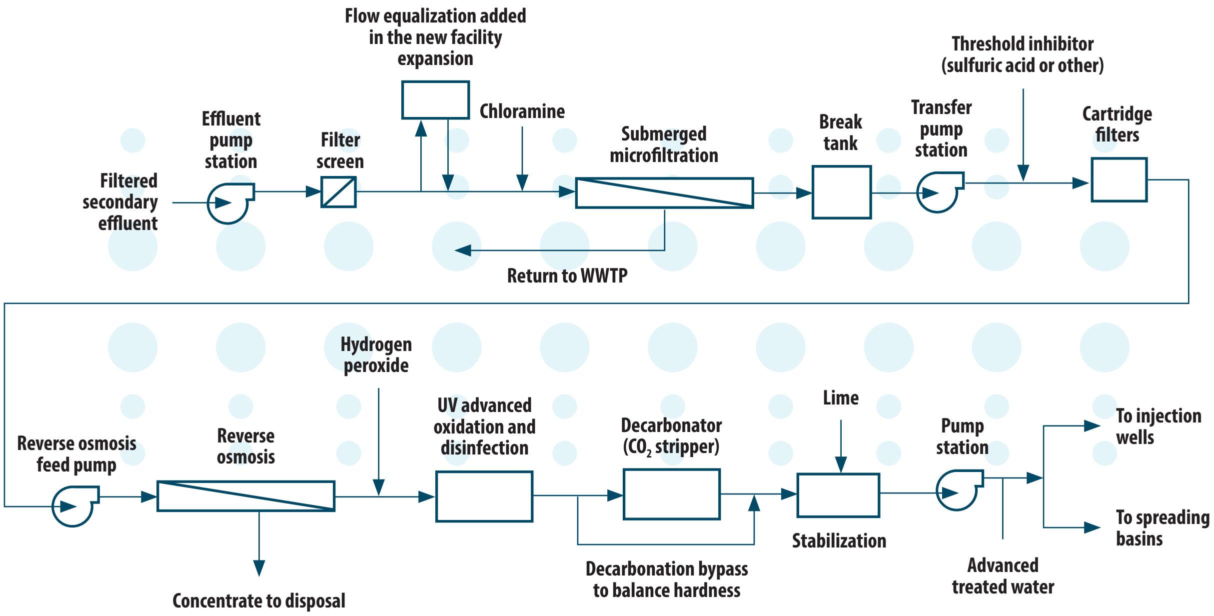
CS2.1 Introduction: Overview and background

The Groundwater Replenishment System is the world's largest advanced water purification system for potable reuse. Launched in 2008, it currently produces 347 MLD of water, with plans to expand to a total production of 492 MLD. In addition, it provides a water supply that is produced using half the energy required to pump water from Northern California – saving enough energy to power 30 000 homes each year.

An IPR project, the Groundwater Replenishment System uses a three-step advanced water treatment process consisting of MF, RO and AOP (UV/H_2O_2) (Figure CS2.1) to purify secondary-treated wastewater that otherwise would be discharged into the Pacific Ocean. The treatment train produces high-quality water that exceeds all state and federal drinking-water standards. After post-treatment stabilization, some of this water is injected into a seawater barrier and the remainder (approximately two thirds) is pumped to recharge basins, where it naturally percolates into the Orange County Groundwater Basin.

The Groundwater Replenishment System is operated jointly by the OCWD and OCSD of Fountain Valley, California.

Figure CS2.1 Flow diagram of the advanced water treatment facility for the Groundwater Replenishment System



Source: Tchobanoglous et al (2015). With permission from the WateReuse Research Foundation (Water Environment & Reuse Foundation report number Reuse-14-20).

CS2.1.1 Potable reuse to achieve sustainable groundwater supplies

The OCWD was created in 1933 by the State of California's Legislature to protect its rights to water from the Santa Ana River and to manage the Orange County groundwater basin, which currently provides 75% of the potable water supply to 2.4 million people in northern and central Orange County.[9] The third most populated county in California, Orange County's population is still on the rise: the north and central regions are projected to grow by more than 300 000 people by 2035. The need for clean, reliable water will grow as well.

[9] The Orange County groundwater basin contains approximately 500 000 acre-feet (162.9 billion US gallons; 616.7 GL) of usable storage water and covers 270 square miles (699.3 square kilometres).

The challenge is that Orange County is located in a semi-arid region of California that receives only about 14 inches (355 mm) of rainfall per year. Local surface water flows from the Santa Ana River traditionally have been used to refill the Orange County groundwater basin, but have dramatically declined in recent years, making it more difficult to provide a sustainable source of local groundwater.

Because of recurrent droughts and the variability of the water supply in the region, the OCWD Board of Directors made the decision to turn to reused water as the primary source of supply for the groundwater basin. Reused water gives OCWD the water supply reliability its groundwater basin needs for continued sustainability.

CS2.1.2 How the Groundwater Replenishment System works: Management, resources and capabilities

The planning, design and construction of the project spanned 11 years, from the initial concept to the start of operations in January 2008. The first of two planned phased expansions was completed in 2015. Specifics on management and resources include:

- **Ownership and management:** The Groundwater Replenishment System advanced water treatment facility (see Figure CS2.1) and its associated distribution, recharge and injection facilities are owned and operated by OCWD. The wastewater collection and treatment facilities that supply secondary treated wastewater to the Groundwater Replenishment System are owned and operated by OCSD, including those for the treatment and disposal of residuals from the system. A series of joint exercise of powers agreements between OCWD and OCSD have governed the cooperative development, financing, construction, operations and maintenance of the scheme. Both OCWD and OCSD shared the initial cost of construction (US$ 481 million).
- **Source of water:** The system purifies secondary treated wastewater produced by OCSD's reclamation plant no. 1. Approximately 75% of the feedwater for the system is supplied via activated sludge facilities operating in a nitrification-partial denitrification mode. The remaining 25% is supplied via trickling filters.
- **Production and capacity:** The system originally had a production capacity of 70 MGD (265 MLD), which is enough water for 850 000 people, as part of the phased expansion plan. Ultimate capacity is projected to be 130 MGD (492 MLD) after the advanced water treatment facility is expanded further and additional wastewater flows are rerouted from ocean discharge for reuse. Since its inception, the scheme has produced more than 155 billion gallons (587 GL) of water. To purchase that same amount in imported water supplies from Northern California or the Colorado River would have cost US$ 318 million.

CS2.2 Approach: Establishment of the potable reuse scheme for the Groundwater Replenishment System

CS2.2.1 Interagency collaboration

Both OCWD and OCSD have had a long history of collaboration preceding the Groundwater Replenishment System. The neighbouring utilities initially developed their reuse partnership over 40 years ago with a project called Water Factory 21, which produced treated recycled water for direct injection into coastal wells, forming a barrier to protect the Orange County groundwater basin from seawater intrusion. Initial planning for Water Factory 21 began in the mid-1960s, and the project came online in 1976.

The treatment process for Water Factory 21 consisted of lime clarification, recarbonation, chlorination, and multimedia filtration, followed by parallel trains of GAC and RO, with the combined product blended with deep well water prior to injection.

By the early 1990s, it had become evident that additional recycled water was needed for the OCWD seawater intrusion barrier. Furthermore, advancements in treatment technology and process control allowed for more efficient recycled water purification processes. At the same time, OCSD was facing the prospect of having to build an additional ocean outfall to contend with increasing wastewater flows and to avoid damage to its existing ocean outfall during peak flow events. It was the confluence of OCWD and OCSD interests in the mid-1990s that set the groundwork for partnering together on the Groundwater Replenishment System.

CS2.2.2 Pilot testing to determine the treatment train

Pilot testing for the scheme was instigated by the need to increase the amount of recycled water being produced by Water Factory 21 from 15 MGD (57 MLD) to 35 MGD (133 MLD). Before OCWD expanded Water Factory 21, it was decided to pilot test newer technologies to optimize treatment plant performance.

The OCWD is located directly adjacent to OCSD, which treats domestic and industrial wastewater. During pilot testing, OCSD approached OCWD with the suggestion of doubling the size of the new facility to 70 MGD (265 MLD) so that OCSD's high-flow events during winter storms also could be treated and either reused or discharged to the Santa Ana River. Doing so would eliminate the need for OCSD to build a second ocean outfall.

The two agencies agreed to jointly build an expanded facility that would provide 70 MGD (265 MLD) of highly purified recycled water for OCWD's seawater barrier and direct recharge into the groundwater basin. The project was named the Groundwater Replenishment System. Pilot- and demonstration-scale testing was completed from 1997 to 1999, with the results being incorporated into the full-scale project design.

During the project development phase and based on pilot testing, the advanced treatment train was determined to consist of the following technologies:

- microfiltration (to remove bacteria, suspended solids and protozoa);
- reverse osmosis (to remove dissolved minerals, viruses and pharmaceuticals); and
- advanced oxidation process (UV) (to provide disinfection and remove low-weight molecular organics, primarily aimed at 1,4-dioxane and NDMA).

CS2.2.3 Phased expansions to produce 130 MGD (492 MLD)

Through sound planning and investment, two expansions were planned from the start of the project to keep costs to a minimum. In fact, a significant portion of the expansion infrastructure was already built into the system when it first came online in 2008.

After nearly eight years of successful operation, the initial expansion came online in 2015 to provide an additional 30 MGD (113 MLD) of reliable water for Orange County. The expansion included:

- 10 new MF cells (bringing the total to 36);
- six new 5-MGD RO units;
- four new UV trains (bringing the total to 13); and
- two 7.5-MG storage tanks to store the overflow of secondary-treated wastewater during daytime peak hours to be processed during the low-flow hours at night.

The benefits of the US$ 142 million initial expansion include:

- increases total output to 100 MGD (379 MLD) at a typical average cost of US$ 520 per acre-foot (US$ 0.42 per kL);
- decreases Orange County's dependence on costly imported water;
- uses half the energy required to move imported water and one third the energy to desalinate seawater;
- provides reliability in a region plagued by cyclical droughts; and
- protects the environment by decreasing the amount of wastewater discharged to the Pacific Ocean and by reusing a precious resource.

In addition, new energy recovery devices will help capture the 3.5 to 4.0 bar loss experienced during the RO process and will, in turn, reduce the amount of energy being used during RO. The new energy recovery devices act as turbochargers and hydraulic pressure boosters, recovering the energy in the concentrate stream and delivering it back to the high-pressure RO feed pumps. They also allow for flux balancing across the three individual RO stages, permitting better operational control.

Further expansion is under way to provide a total production of 130 MGD (492 MLD), and the Groundwater Replenishment System will continue to invest in projects that create long-term water reliability for the region.

CS2.3 Control measures

CS2.3.1 Orange County Sanitation District source control programme

Source control for the system is provided by OCSD. The purpose of the source control programme is to manage the quality of raw wastewater received by OCSD, thereby ensuring pollutants and chemicals of public health concern are not discharged to local sewers in quantities that would compromise the quality of water produced via unacceptable interference or pass through of the wastewater and advanced water treatment processes. Both industrial and non-industrial discharges are regulated and permitted.

The source control programme follows State of California regulations for groundwater recharge reuse projects and includes the following:

- Assessing the fate of state-specified contaminants through the wastewater and advanced water treatment processes.
- Chemical and contaminant source investigations and monitoring focused on state-specified chemicals.
- Outreach programmes to industrial, commercial, and residential communities to manage and minimize the discharge of contaminants at the source.
- Current inventory of chemicals and contaminants (including new chemicals resulting from new sources or changes to existing sources) that may be discharged into the wastewater collection system.

CS2.3.2 Treatment strategy: Multiple barriers

The Groundwater Replenishment System employs the multiple-barrier approach to protect public health from acute health risks associated with exposure to pathogenic microorganisms, as well as acute and chronic health risks associated with chemicals.

- **Pathogens:** The MF + chloramine process has been credited with a 4-log reduction for *Giardia* and *Cryptosporidium*, as well as 1-log reduction for viruses. The RO and AOP (UV/H_2O_2) systems have been granted 2-log and 6-log reduction, respectively, for these pathogens.
- **Chemicals:** The control of chemical risk begins with the source control programme administered by OCSD. The RO system, featuring modern thin film composite polyamide membranes, is a robust chemical barrier, effectively removing a broad range of both inorganic and organic chemicals. The AOP (UV/H_2O_2) system provides a supplementary barrier to address low molecular weight, uncharged trace organic compounds that are not completely removed by RO.

CS2.3.3 Advanced treatment process validation

The validation of the advanced treatment processes (i.e. MF, RO, AOP [UV/H_2O_2]) for the scheme has occurred at different times using a variety of approaches:

- **Microfiltration:** The pathogenic microorganism removals for the MF process have been previously validated through a combination of manufacturer testing and documentation of on-site performance for the indigenous removal of *Giardia*, *Cryptosporidium* and coliphages (as a surrogate for viruses).
- **Reverse osmosis:** The bulk feed and permeate from the RO system are continuously monitored for TOC and electrical conductivity using online analysers (the real-time TOC removal across the RO process is consistently in excess of 2 log, providing a validation of the RO pathogen removal credits). RO performance has been validated further using indigenous coliphages monitoring, with monthly bulk RO permeate analysis via USEPA methods 1601 and 1602, resulting in no quantifiable detections over the first eight years of operations.
- **Advanced oxidation process (ultraviolet/hydrogen peroxide):** The UV system was validated for pathogen log reduction using an MS2 coliphage seeding study conducted in 2004 at a 5 MGD facility operated during the interim period between the end of Water Factory 21 operations and the onset of Groundwater Replenishment System operations. Additional validation for NDMA and 1,4-dioxane removal were conducted during the start-up commissioning of the new facility in late 2007.

CS2.3.4 Environmental buffer: Orange County groundwater basin

The Orange County groundwater basin aquifer system acts as the storage and transport system and the environmental buffer for the Groundwater Replenishment System. There have been indications of at least temporary mobilization of some contaminants in the aquifer from the highly treated water addition, however, these have become stabilized by:

- dilution/blending;
- time to respond to potential treatment plant upsets resulting in the recharge/injection of off-spec water; and
- additional treatment.

The regulations for groundwater replenishment with recycled water adopted by the State of California require a minimum of two months of subsurface response retention time within the aquifer prior to extraction for potable use. The Groundwater Replenishment System has been approved for a response retention time of three months, and also receives a 3-log virus reduction credit for subsurface retention (1-log reduction per month). Typically, the actual subsurface travel time between the points of recharge/injection and extraction is in the order of many years.

CS2.4 Water quality monitoring

CS2.4.1 Operational monitoring

The primary measure of the performance of the treatment plant is based on water quality, including:

- **Turbidity:** Used as bulk surrogate for suspended solids, turbidity is monitored continuously using online instrumentation across the MF and RO processes to help confirm membrane integrity.
- **Total organic carbon:** Used as bulk surrogate, TOC monitoring is required to document the effective removal of organics of wastewater origin.
- **Total nitrogen:** Monitoring is required to demonstrate total nitrogen control, given the prevalence of nitrogen species in wastewater.
- **Total dissolved solids:** TDS is used as a bulk surrogate to demonstrate the effective control and removal of inorganic species, especially salts. Nearly all TDS removal at the Groundwater Replenishment System occurs during the RO process, with removal regularly exceeding 95%. Laboratory testing of TDS is supplemented with continuous online measurement of conductivity in the feed and permeate flows of each individual RO unit.
- ***N*-Nitrosodimethylamine:** NDMA is the primary chemical target of the UV component of the AOP/UV system, which was originally designed for 1.2-log reduction of NDMA via UV photolysis.

These parameters provide an indication of overall treatment plant performance, especially regarding the RO and AOP processes. Many of the water quality requirements go beyond those for primary and secondary drinking-water standards. Critical water quality requirements defined in the operating permit include:

- Turbidity (in RO permeate, less than 0.2 NTU more than 95% of the time in any 24-hour period; and less than 0.5 NTU at any time).
- Total organic carbon (in final product water, less than 0.5 mg/L in recycled water over a 20-sample running average, with samples collected at least weekly).
- Total nitrogen (in final product water, less than 5 mg/L, based on twice weekly monitoring).
- *N*-Nitrosodimethylamine (in final product water, no formal permit limit, but OCWD maintains a voluntary goal of less than 10 ng/L).

The treatment plant also removes CECs. Formal monitoring requirements for CECs in potable reuse projects have been adopted by the State of California (SWRCB, 2013), and additional future regulations are possible. The CECs most often found in wastewater include:

- pharmaceuticals (e.g. acetaminophen, ibuprofen, caffeine, carbamazepine, gemfibrozil, primidone, and sulfamethoxazole);
- flame retardants (e.g. tris(2-chloroethyl) phosphate); and
- pesticides (e.g. DEET, diuron and triclosan).

None of these chemicals, nor any other CECs tested, are detected in measurable concentrations in the advanced treated water after AOP/UV.

CS2.4.2 Verification

The OCWD must submit quarterly and annual reports to the regional board, documenting treatment plant performance, monitoring results, and compliance with permit limits and conditions. Regional board staff also perform periodic unscheduled on-site inspections and audits of the facilities.

One condition of the regional board permit is the establishment and regular meeting of an expert peer review panel (referred to as the Groundwater Replenishment System Independent Advisory Panel) to provide regular review of operations and water quality (see also Section CS2.6). The panel is administered by the NWRI, a non-profit research organization based in Southern California that specializes in organizing and managing expert panels to address complex projects, policies and technologies in the water industry. Members of the panel include experts in the fields of toxicology, chemistry, microbiology, epidemiology, hydrogeology, public health, engineering and environmental protection.

Since its establishment in 2004, the full panel has met annually (with smaller subcommittee meetings on specific topics held between annual meetings) during the design, start-up and regular operation of the system. Regulators and other interested parties are invited to attend these meetings. The product of each meeting is a report containing findings and recommendations of the panel that are transmitted to OCWD, OCSD, regulators and other interested stakeholders.

CS2.5 Incident management: Response plan and critical control points

It is intended that the Groundwater Replenishment System will always operate on the condition that it causes no impairment to the groundwater basin. The OCWD's goal is to produce the highest recycled water quality for groundwater recharge in compliance with the regional board permit.

The primary safeguard is that it is not absolutely necessary to operate the Groundwater Replenishment System for the production of purified recycled water 100% of the time. Under any emergency condition, the production of purified recycled water can be suspended until the problem is corrected; under wastewater current flows, the OCSD outfall system can discharge all non-reclaimed wastewater. Recycled water produced by the Groundwater Replenishment System also can be diverted and returned to OCSD for discharge to the ocean. If a plant outage did occur for an extended period of time, then alternate potable supplies are available to supply the seawater intrusion barrier.

Both OCWD and OCSD have developed a joint agency response plan to respond to unexpected water quality results in feedwater or product water that cause an exceedance of the permit limit or otherwise indicate a significant reduction in water quality. The response plan sets coordinated actions for multiple departments (e.g. laboratory, process engineers, permitting specialists, field inspectors) across both agencies to determine the source of the water quality problem and take appropriate actions.

Furthermore, the CCP for the Groundwater Replenishment System RO permeate TOC is continuously measured and compared with both the historical average and the 0.5 mg/L regional board permit limit. In the event of a sustained increase in TOC above the historical norm, a series of investigatory actions are first undertaken to discern the reason for the elevated trend (e.g. an increase in RO feed TOC, membrane integrity issues), as well to test for the specific organic constituent(s) responsible. Should TOC reach a level where a violation of the 20-sample running average permit limit of 0.5 mg/L is imminent, then the facility would be shut down. These protocols are included in the operations optimization plan, which describes operations, maintenance, monitoring and associated analytical methods, including the use of CCPs. The operation optimization plan is a requirement of the Groundwater Replenishment System permit and associated regulations.

CS2.6 Public outreach and stakeholder engagement

Outreach to the public and stakeholders has been a priority since the beginning of the project. Early on, OCWD and OCSD formed a joint steering committee to develop policies and make decisions regarding the planning and implementation of the system. At its first meeting in March 1997, the joint steering committee identified public outreach as a high priority. The decision to make public outreach a priority at the beginning of the project was one of the keys to the success. The comprehensive public outreach and education programme for the Groundwater Replenishment System is described in detail in Appendix 4.

CS2.7 Governance

The Groundwater Replenishment System operates under a permit originally approved by the California Regional Water Quality Control Board, Santa Ana Region (Regional Board) 2004 and issued to OCWD, with subsequent amendments in 2008 and 2014. The original basis for the permit was the draft groundwater replenishment (GWR) regulations for indirect potable reuse developed by the State of California,[10] which included requirements for treatment, blending, underground retention time, monitoring control of pathogens, and the control of regulated and unregulated chemicals.

Because the regulations were in draft format at the time and had not been formally adopted by the California Department of Public Health,[11] OCWD worked closely with the Department of Public Health early on in the project to develop criteria for what chemical and microbial water quality constituents would be tested and the required detection limits. The discharge permit was then obtained from the Regional Board, which would consult with the California Department of Public Health to develop the specific requirements.

In response, OCWD engaged an independent advisory panel (Section CS2.4.2) to assist OCWD and the Department of Public Health in the development of the permit conditions. The activities of the panel assisted in developing the conditions for the permit and were instrumental in removing some of the regulatory hurdles that could have prevented the system from being implemented in a timely manner.

Staff from the Department of Public Health reviewed the project during a formal public hearing held in 2003, resulting in "findings of fact and conditions" that were incorporated into the Regional Board permit. Based on the permit, the final product water must meet State of California primary drinking-water standards (which are equivalent to or more stringent than the federal standards set by the USEPA) during required quarterly testing. In addition, quarterly monitoring is required for unregulated chemicals, with more frequent monitoring required for total coliform bacteria, TOC and total nitrogen. The State of California later established requirements for monitoring CECs for recycled water recharge/injection projects via the State Water Resources Control Board's 2013 Amendment to the 2009 Recycled Water Policy.

CS2.8 Conclusions and lessons learned

- **Establish the need for potable reuse:** OCWD had been practising potable reuse for nearly 40 years, but needed to expand its efforts to provide a sustainable source of water for the groundwater basin.
- **Develop health-based targets:** Health-based targets for the discharge permit were developed by the State of California with the advice of an independent advisory panel organized by NWRI.
- **Establish plans to ensure water safety:** Both an operation optimization plan and CCPs (i.e. continuous online TOC and turbidity testing) were developed.
- **Build credibility through input from independent experts:** The NWRI independent advisory panel has met annually in person since 2004, with a number of smaller subcommittee meetings in between to provide expert review of operations and water quality during the pre-design, start-up and implementation of the project.

[10] Regulations for groundwater replenishment using IPR were finalized and formally adopted by the State of California on 18 July 2014, under "Title 22, Division 4, Chapter 3: Water Recycling Criteria" of the California Code of Regulations.

[11] As of 1 July 2014, the Drinking-water Program of the California Department of Public Health was officially transferred to the California State Water Resources Control Board and renamed the Division of Drinking-water.

- **Work closely with regulators:** At the time the Groundwater Replenishment System was implemented, final groundwater recharge regulations were not available; however, groundwater regulations now exist for IPR through the Division of Drinking-water of the State Water Resources Control Board.
- **Garner public acceptance early and proactively:** OCWD implemented a robust public outreach campaign early in the project, which resulted in no active opposition. Outreach was a key to the system's success.
- **Overall conclusion:** Potable reuse is necessary to ensure water supply reliability in areas around the world that lack adequate water resources.

CS2.8.1 National and international recognition

The Groundwater Replenishment System has been awarded over 40 awards, including the 2008 Stockholm Industry Award and the 2014 Lee Kuan Yew Water Prize.

CS3 Upper Occoquan Service Authority potable reuse project in Virginia, United States of America

CS3.1 Introduction

The Occoquan Reservoir is a critical component of the raw water supply for approximately 1.5 million residents of northern Virginia, a highly urbanized region located on the southwestern periphery of the USA national capital, Washington, DC. Treated wastewater directed to the reservoir represents a significant supplement to the potable water supply yield. The project has operated successfully for nearly four decades.

In 1950, a low head dam was constructed on the Occoquan River to serve local water supply needs. In 1957 the low head dam was replaced with a larger dam which created the Occoquan Reservoir. By 1967 ownership of the system passed to the Fairfax County Water Authority (now Fairfax Water), which continues to operate the system, including the Occoquan Reservoir, the dam and outlet works, and the drinking-water treatment facilities.

Occoquan Reservoir (source: Roger W Snyder).

At the time of the large dam completion, the full pool storage was estimated to be 37 million m^3 (37 GL), with a safe water supply yield of approximately 189 300 m^3/d (189.3 MLD).

In the 1960s, a transformation began that changed the watershed from largely rural-agricultural in character to one of predominantly urban/suburban uses. Unprecedented growth in the northern Virginia suburbs of Washington DC, was accompanied by major expansions of residential and commercial development which extended into the Occoquan Watershed, and began to impact reservoir water quality (Robbins, 1993).

CS3.1.1 Principal drivers for water reuse

Concern over degradation of reservoir water quality led to a series of scientific studies to determine causes, and to develop plans to restore and provide for future protection of the water supply. Urban development had already resulted in unplanned indirect potable reuse, and 11 small conventional WWTPs were discharging to reservoir tributaries. Coupled with the effects of agricultural runoff and increasing urban drainage, poorly treated wastewater threatened the viability of the Occoquan Reservoir for public water supply. Typical water quality problems included frequent and intense summer blooms of cyanobacteria, dissolved oxygen depletion and subsequent generation of sulfide during thermal stratification, and periodic fish kills. Increased costs were incurred in water treatment due to the presence of algal mats in raw water. In addition, algae-related taste and odours required treatment with powdered activated carbon. Increased formation of DBPs also occurred. Finally, studies reported enteric viruses in the reservoir, indicating contamination from wastewater discharges (Robbins, 1979).

Several solutions were proposed, including a conventional approach to treat the wastewater centrally but ultimately export it outside the watershed. It was concluded that the net loss of water from the watershed would reduce system resilience during times of drought. A DPR option was considered, in which wastewater would be treated centrally at a (then) state-of-the-art facility, and pumped directly to the downstream drinking-water treatment plant for additional treatment and distribution. Although the option would have preserved the treated wastewater for use within the region, it was opposed by public health officials and received little public support. Another alternative was IPR, where watershed wastewaters would be treated centrally using the highest performance technologies then available, and subsequently released to a direct tributary of the Occoquan Reservoir to supplement the raw water supply.

After extensive review, the Virginia State Water Control Board, in consultation with the Virginia Department of Health, adopted an IPR solution to protect the drinking-water supply and to supplement its yield. The Policy for Wastewater Treatment and Water Quality Management in the Occoquan Watershed, more commonly known as the "Occoquan Policy" (SWCB, 1971), mandated a new framework for planned potable reuse. The decision resulted in the first full-scale planned use of treated wastewater for the purpose of supplementing a surface water supply in the USA. The Occoquan Policy also established treated wastewater treatment standards that had never been previously achieved by a water reclamation facility.

After nearly four decades of successful operation, the project is seen globally as a pioneering effort in potable reuse. Although major advances in treatment technology have occurred in the ensuing years, the early application of innovative physical-chemical-biological treatment processes of the day has stood the test of time. The in-basin solution for the Occoquan Watershed validated the foresight and vision of early decision-makers, including local governments, water reclamation and water treatment agencies, and state and federal regulators.

CS3.2 Approach: Establishment of potable reuse

Fairfax Water was already in existence at the adoption of the Occoquan Policy (Fairfax Water, 1975), and provided finished drinking-water from the Occoquan Reservoir. The Occoquan Policy also mandated the creation of the UOSA, to provide for collection and reclamation of wastewater; and the OWMP, to continuously monitor the watershed and reservoir with a view to providing independent water quality assessments and advice on protective measures for the water supply.

In the 1970s UOSA began the design of the new regional reclamation system, and the OWMP began baseline monitoring in the watershed. In mid-1978, UOSA started up the water reclamation plant (WRP), initially producing about 18 900 m^3/d (18.9 MLD) of treated wastewater. The water quality of the Occoquan Reservoir rapidly exhibited dramatic improvements.

Although the plant was originally constructed with a water reclamation capacity of 56 800 m^3/d (56.8 MLD), discharges were restricted until monitoring results clearly showed the desired improvements in reservoir water quality. By 1985, watershed growth resulted in an expansion to 85 200 m^3/d (85.2 MLD). It was also clear that continued growth, coupled with confidence in the reuse project, would result in demand for much greater expansion (Robbins, 1993).

Modelling results led to the unanticipated finding that contributions of high-quality treated wastewater would be necessary to offset anticipated increases in pollution from nonpoint sources and urban runoff. Further, it was concluded that importing wastewater for treatment at the UOSA plant would be desirable to offset future water quality impacts of non-point pollution from urban stormwater (Chen & Gomez, 1988). After a decade of operation, the initial solution proposed to export wastewater from the basin had been supplanted by a recommendation to import wastewater into the watershed

for reclamation by UOSA to not only further supplement yield, but to also enhance water quality.
After several expansions, in 2004 the UOSA WRP had a capacity up to 204 400 m^3/d (204.4 MLD), with an anticipated buildout capacity of 246 000 m^3/d (246 MLD).

CS.3.3 Control measures for wastewater reclamation and water treatment

The original project and subsequent expansions have all viewed the UOSA WRP within the context of the multiple-barrier approach to protect the Occoquan drinking-water supply. Within the watershed, practices include wastewater source control and collection, water reclamation, local storage, environmental buffers and storage, raw water abstraction and treatment, and management of potable water distribution.

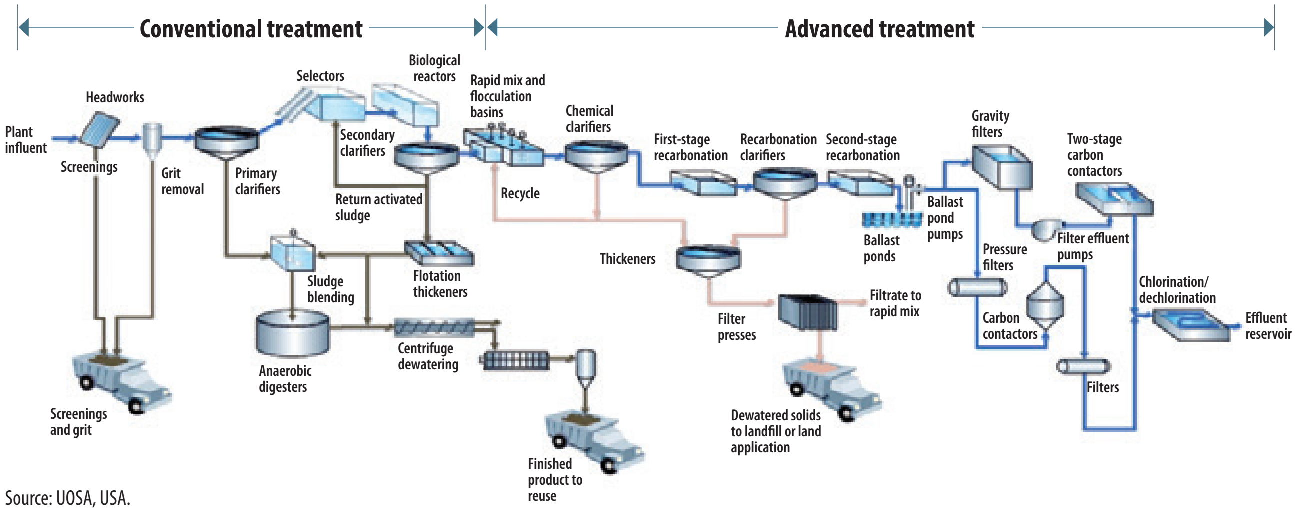
In addition to the conventional and advanced water reclamation processes, the system incorporated a range of reliability features. Retention basins at pump stations and at the WRP provide storage for high flow conditions, as well as for emergencies and planned maintenance. All major mechanical and electrical components have at least one backup unit on ready standby. Electric power is fed from two independent grid sources, and on-site power generation is available to power the entire plant. Pump stations have similar redundancies, including backup power features. All plant processes and the collection system are monitored by a computerized supervisory control system, and most pump station and plant processes are automatically controlled by the computer network (Asano et al, 2007).

An aerial view of the plant is shown below. The process flow diagram for the facility is shown in Figure CS3.1. At the present time, major treatment processes include (Angelotti, 1995; Angelotti et al, 2005):

- conventional preliminary and primary treatment;
- advanced secondary treatment including BNR capabilities;
- high pH lime clarification for phosphorus and metal removal and virus inactivation;
- two-stage recarbonation with intermediate settling for metal and hardness removal;
- multimedia filtration for turbidity, suspended solids and protozoan cyst removal;
- deep GAC beds for additional filtration and removal of trace organics;
- free chlorine disinfection for additional pathogen destruction; and
- dechlorination.

MH Robbins Jr water reclamation plant operated by UOSA (source: UOSA, USA).

Figure CS3.1 Process schematic of the Upper Occoquan Service Authority water reclamation facility



Source: UOSA, USA.

Except some changes in nitrogen management strategies to meet water quality management objectives in the Occoquan Reservoir and ultimately, the Chesapeake Bay, the basic UOSA WRP process configuration is largely unchanged since the design concept was developed in the mid-1970s. The biological-physical-chemical process train included elements that were well known in both water treatment and wastewater treatment operations at the time, but had not been integrated into a full-scale single reclamation facility.

Product water is discharged to a 681 400 m^3 (681.4 ML) impoundment on the plant site prior to release into a tributary of Bull Run Creek, which flows on directly to the Occoquan Reservoir. The on-site reservoir is the first of the natural barriers of the system, and provides a mixing volume to mediate any short-term variability in the product water.

The Occoquan Reservoir is a run of the river impoundment, and as a result, has high seasonable variability in residence time, which is further affected by the significant withdrawals for drinking-water production. The average residence time is less than 30 days, but storm flows, and the combined effects of drought and pool drawdown, can produce very large departures from that value. For example, 2 cm of runoff over the watershed area would result in a complete replacement of the reservoir volume (Virginia Tech, 1994).

In 2006, existing treatment facilities using the Occoquan source were replaced by the Frederick P Griffith Jr drinking-water treatment plant. The new plant represented a major upgrade in both treatment technology and included the following processes:

- raw water screening and pumping
- enhanced metal salt coagulation, flocculation and settling
- ozonation
- deep bed BAC filtration
- chloramination.

The new facility was designed to take advantage of the enhanced yield of the Occoquan system resulting from treated wastewater contributions. Currently, the drinking-water plant has a treatment capacity of 454 000 m^3/day (454 MLD).

CS3.4 Water quality monitoring

The product water from the UOSA WRP must meet performance standards set by the Virginia Department of Environmental Quality, which are summarized in Table CS3.1, along with typical performance values for the plant.

In addition to laboratory analyses required to assess plant performance, continuous analysers are used to provide additional process information. Filters are equipped with turbidimeters to ensure that particle removal is consistent with good protozoan cyst removal. Residual analysers and flowmeters are installed at chlorine contact basins to verify that contact times and chlorine concentrations are adequate for pathogen kill or inactivation (USEPA, 2012a).

Annual acute and chronic bioassays are conducted to verify that the product water has no observed effect on target organisms. Annual testing is also performed to confirm that product water meets the latest requirements of the USEPA national primary and secondary drinking-water standards. Periodic evaluations are also performed to determine if pharmaceuticals and personal care products or other compounds of interest are present at levels of concern in the treated wastewater. More than 300 trace organic compounds are assayed in both the product water and Occoquan Reservoir tributaries. Over 90% of the recorded results in the product water are non-detects. The WRP product water consistently meets conventional drinking-water standards except seasonally for TDS and nitrate. Recent evaluations have also shown that the quality of the WRP product water with respect to trace organic compounds is consistent with proposed criteria for DPR (WRRF & NWRI, 2013), supporting the conclusion that no significant risk to public health is imposed by the UOSA contribution (Angelotti et al, 2014).

In association with the OWMP, a sophisticated, complexly linked watershed and reservoir computer model has been developed which may be used to predict water quality changes resulting from future changes in land use, character or quantity of treated wastewater flows, or watershed hydrology (Xu et al, 2007). The modelling system is being adapted to aid in managing the water supply system under anticipated climate change scenarios.

Table CS3.1 Discharge standards for the Upper Occoquan Service Authority product water

Parameter	Monthly average concentration	Performance standards		Typical performance
		Weekly average concentration	Units	
Chemical oxygen demand	10	25	mg/L	6–9
pH	6–9[a]	N/A	pH units	7.1–7.7
Total suspended solids	1.0	2.5	mg/L	0.3–0.6
Turbidity	0.5	1.25	NTU	0.1–0.2
Total Kjeldahl nitrogen	1.0	2.5	mg/L	0.3–0.5
Methylene blue active substances	0.10	0.25	mg/L	0.01–0.05
Escherichia coli (geometric mean)	<2	N/A	n/100 ml	Not detected
Total residual chlorine (after dechlorination)	0.008	0.010	mg/L	Not detected
Total phosphorus	0.10	0.25	mg/L	0.04–0.09

[a]Not monthly average. Any daily reading must fall within the range of 6–9 pH units.
Source: UOSA (2011).

CS3.4.1 Independent assessment (auditing)

A significant requirement of the Occoquan Policy (SWCB, 1971) was to establish a water quality monitoring programme independent of both the water reclamation agency and the drinking-water provider. Because of the need to evaluate water reclamation performance within the context of other watershed activities (e.g. agriculture and urban land uses), the OWMP operates and maintains a network of nine stream monitoring stations, 14 recording rain gauges, and eight reservoir monitoring stations. The OWMP also provides an independent review of UOSA facility performance and acts as a source of independent information and analysis for all watershed stakeholders. Local programmes to manage urban stormwater pollution were developed well in advance of regulatory requirements in order to protect the investment in high performance water reclamation.

CS3.5 Public outreach

When the water reclamation programme was first proposed, public meetings and hearings were conducted to explain the project, and to provide an opportunity for community feedback. Following start-up of the WRP, UOSA has maintained an active, tour-based, educational programme to explain the potable reuse strategy. Likewise, Fairfax Water maintains an active programme of community outreach and provides tours and other educational activities to engage with the public. Both agencies, along with the OWMP, maintain publicly accessible websites to provide relevant information.

On occasion, issues have arisen that resulted in a need for technical advisory groups, citizen action committees, and other specialized task forces. These have been variously composed of agency stakeholders, local government officials, community representatives, water experts and interested citizens (Ruetten, 2004). Examples of issues addressed include: reducing the zoning density of certain subwatersheds to protect water quality; siting of a major semiconductor fabrication facility within the WRP service area; and proposals for consumptive uses of treated wastewater for cooling water at a proposed power generation facility. The last proposal (consumptive use) prompted significant debate about the potential loss of treated wastewater flow into the drinking-water supply.

CS3.6 Governance

Both Fairfax Water and UOSA are independent public service authorities, and are governed by appointed boards of directors, who are representatives of their community constituencies.

The OWMP has an oversight committee comprised of members from the USEPA, Virginia Department of Conservation and Recreation, Virginia Department of Health, an academic expert from a state university in Virginia and an external consultant. The OWMP oversight committee meets annually to review watershed water quality data, as well as water reclamation and drinking-water plant operations. The committee maintains an advisory function to the Virginia Department of Environmental Quality, which is the permitting agency for the WRP.

Because of the importance of the treated wastewater in protecting source water quality and enhancing yield, an operational framework has evolved that is based on close collaboration among five principal agencies:

- Upper Occoquan Service Authority: Wastewater Reclamation Authority
- Fairfax Water: Potable Water Production Authority
- The Occoquan Watershed Monitoring Program: Independent Assessment Entity
- The Virginia Department of Environmental Quality: Water Reclamation Regulator
- The Virginia Department of Health: Drinking-water Regulator.

Each entity has a defined role in the implementation of the Occoquan potable reuse programme. Basic regulation is provided by the Departments of Environmental Quality and Health, and in accordance with federal requirements. The treatment authorities, UOSA and Fairfax Water, are responsible for planning, operating and maintaining treatment systems that meet regulatory requirements, and the independent assessment entity provides process performance oversight and water quality assessment. Although each entity has its own institutionally defined role, each is also engaged in the overall objective of protecting and enhancing the Occoquan Reservoir as a raw water supply for the region.

CS3.7 Conclusions

UOSA provides reliable, high-quality treated wastewater to the Occoquan Reservoir, and Fairfax Water relies on that contribution as a key component of its water supply plan. The UOSA flows are of particular importance during drought conditions. On average, the treated wastewater represents approximately 9% of the annual average inflows to the reservoir, but during periods of drought, the contribution may exceed 90%. During such periods, pool drawdowns substantially shorten the reservoir residence time.

The Occoquan IPR programme has been in successful operation for nearly four decades. In the 1960s, it was widely accepted that the unplanned IPR was a key problem in the historical degradation of the water supply, and had already resulted in a temporary sewer connection ban in the watershed pending development of a long-term management plan.

The proposal to address the problem with a technically sound planned potable reuse project was readily understood (Ruetten, 2004), and although water quality was a major driver, it was also recognized that directing treated wastewater flows to the reservoir would be a significant asset for future water supply needs (WEF & AWWA, 2008).

Because of the substantial improvements to the quality of the raw water supply, public opposition was much lower than has been historically experienced with other potable reuse proposals. There was, however, widespread local concern about the cost implications for ratepayers, although that has become less prevalent over the decades of successful programme operation.

Further reading

Angelotti RW (2010). Sustainable water practices surrounding indirect potable reuse within the Occoquan Basin. Proceedings 2010 Sustainable Water Management Conference and Exposition, Albuquerque (NM). American Water Works Association, WateReuse Association and Water Research Foundation.

Angelotti RW, Maheiu E, Kulik W (2008). Strategies to minimize impacts of a microchip manufacturer on a potable water reuse system. Proceedings 23rd WateReuse Symposium, Dallas (TX).

FCWA (2011). Fairfax Water. Fairfax County Water Authority. http://www.fcwa.org/ (accessed 22 May 2017).

Rimer A and Miller G (2011). Seasonal storage of reclaimed water. Report for WRF-09-05. Alexandria (VA): WateReuse Research Foundation and U.S. Bureau of Reclamation. 71–82.

Schimmoller L and Angelotti RW (2011). Indirect potable reuse without reverse osmosis: Using GAC-based treatment to improve sustainability and reduce cost. Proceedings of the 2011 Potable Reuse Conference, Hollywood (FL). Alexandria (VA): WateReuse Association.

CS4 Water reuse in Singapore – NEWater

CS4.1 Overview and background

Singapore is land scarce and highly urbanized. With about 5.6 million people living on an area spanning just 719 km^2 (Department of Statistics, Singapore), there is limited land available for collection and storage of rainwater. Thus, despite the 2400 mm of rain that it receives annually, Singapore has to depend on diverse water sources to meet its demand of 1.95 million m^3/day (1.95 GL/day) (PUB, 2016).

Known as the "four national taps", these water sources comprise water from local catchment areas; imported water from Johor, Malaysia; high-grade treated wastewater meeting drinking-water standards, referred to as NEWater; and desalinated water. The PUB manages the integrated supply system, as well as all other aspects of the water loop, including water demand management, watershed management and the collection and treatment of sewage, which is termed "used water".

CS4.2 Approach: Establishment of potable reuse

In 1974, the first water reclamation pilot plant was built to evaluate various technologies for water reuse, including RO, but this was found to be too costly (Tan et al, 2012). The PUB and what was then the Ministry of the Environment continued to monitor the technology trends for improvements in reliability and cost-effectiveness. In 1998, two engineers were sent to the USA to evaluate water reuse projects such as the OCWD (Water Factory 21) and Upper Occoquan Sewage Authority. Upon finding the water reuse processes viable, a team was formed to pilot test its application in Singapore's context (Tan et al, 2012).

The Singapore water reclamation study (NEWater study) was conceptualized in 1998 to determine the suitability of using treated wastewater for planned IPR (PUB, 2002). A two-year study from 2000 to 2002 was carried out that comprised the following three main components:

- 10 000 m^3/day (10 MLD) demonstration plant utilizing MF, RO and UV to produce NEWater;
- sampling and monitoring programme to assess water quality; and
- health effects testing programme to determine the long-term safety of NEWater.

A panel of local and foreign experts was appointed by the PUB/Ministry of Environment to provide independent advice on the study and evaluate its findings. In 2002, the panel concluded that NEWater was safe for potable use and recommended using the IPR approach to provide an environmental buffer which allowed the NEWater to re-naturalize and trace minerals to be reintroduced, by blending with reservoir water (PUB, 2002).

The first two NEWater plants, in Bedok and Kranji, were commissioned in early 2003, supplying 72 000 m^3/day (72 MLD). Today, the supply capacity of 760 000 m^3/day (760 MLD) from four plants can meet up to 40% of Singapore's total water demand (PUB, 2017). The two newer plants, located at WRPs in Ulu Pandan and Changi, were developed under the design-build-own-operate model, where a private company supplies water to PUB, subject to a stringent set of quality standards.

From its earliest days, NEWater has been supplied mainly for direct non-potable use by water-intensive industries such as wafer fabrication plants and petrochemical industries, as well as in cooling towers of commercial and public buildings. This frees up potable water for domestic consumption. A small amount of NEWater is injected into water reservoirs and supplied for IPR. Usually, IPR constitutes about 2–3% of water demand but this can be increased substantially to more than 10% when larger quantities of NEWater are injected to supplement reservoir supply during dry spells.

NEWater is supplied through a dedicated pipeline network. The network began as separate clusters where pipelines were laid from each NEWater plant to specific groups of water-intensive industries, while supplying other non-domestic users (such as commercial buildings) along the way. Off-takes were laid to the nearest water reservoir in each cluster for IPR. In 2012, an island-wide transmission system was completed, linking the four NEWater plants and various supply clusters. This improved supply reliability and allowed for greater flexibility in managing NEWater supply for both direct non-potable use and IPR.

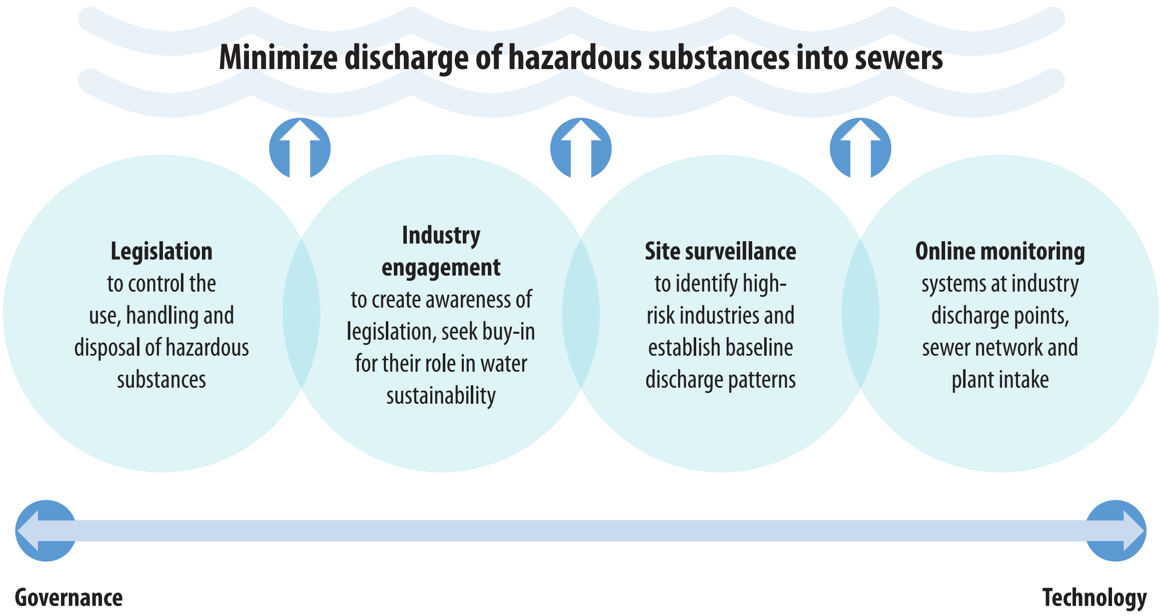
CS4.3 Control measures from source to tap

A system of multiple barriers, comprising source control and treatment, coupled with engineered storage, environmental buffers and online monitoring is in place to safeguard the quality of NEWater for IPR.

CS4.3.1 Source control

While most of the used water collected is from municipal sources, industries also discharge used water into the sewers, posing a greater risk to the quality of used water for NEWater production. PUB manages this through a multi-pronged approach as illustrated below.

Figure CS4.1 Multi-pronged approach to source control for water reuse in Singapore



Source: PUB, Singapore.

Legislative power is an important lever but the key to effective management of used water quality lies in having a comprehensive understanding of the catchment profile, which can only be achieved through continual engagement of industries and close monitoring of used water quality throughout the sewer network.

PUB relies on online VOC sensors located at strategic points in the network to provide early warnings of illegal discharges of VOCs, such as when an industry discharges cleaning agents, used oils or solvents into the sewers. Although infrequent, such incidents require prompt intervention as most VOCs cannot be effectively removed by the NEWater process. They could affect water quality and have potentially harmful effects on human health. This early warning allows the WRP downstream to divert affected treated wastewater away from NEWater production. In addition to VOC sensors, a compact microbial electrochemical sensor has been successfully developed, after field testing, for online monitoring of used water toxicity. It has been installed at five factories to further optimize performance.

CS4.3.2 Treatment

Used water undergoes treatment in the WRPs. Primary clarification is followed by secondary treatment, which includes the ASP and final clarification. The WRPs are critical in providing a consistent supply of good quality wastewater, which not only leads to good NEWater quality, but also helps to minimize fouling of the membranes used for NEWater production.

At the NEWater plant, treated wastewater undergoes MF or UF followed by RO and finally UV disinfection. Furthermore, the pipe and valve configuration allows the permeate from each RO train to be recycled back to the RO feed tank, achieving different levels of dilution as required to maintain product water quality during instances of usually high salt content in the source water. Table CS4.1 summarizes the treatment processes involved in NEWater production from used water.
PUB is installing MBRs as part of WRP upgrading. For future expansions of NEWater production, MBR filtrate will be fed directly to the RO process for NEWater production. The MBR-RO process has been pilot tested and found to be more robust in handling shock loadings and discharges, while producing better quality NEWater (Tao et al, 2006).

Table CS4.1 Treatment processes for water reuse in Singapore

Plant	Process	Main purpose
Water reclamation plant	Primary clarification	Reduction of suspended solids, biological content, large organic substances, etc.
	Secondary treatment (activated sludge process and final clarification)	
NEWater plant	Microfiltration/ultrafiltration	Removal of suspended solids, colloidal material, bacteria, protozoan cysts
	Reverse osmosis	Removal of viruses, dissolved organic and inorganic substances
	Ultraviolet disinfection	Safety back-up to inactivate microorganisms in the unlikely case of breach of RO membrane integrity

CS4.3.3 Storage and conveyance

The NEWater plant design includes a product water storage tank with a minimum nine-hour retention capacity. This provides adequate response retention time in the event of contamination or a disruption in the treatment process. Water quality in the tank is continuously monitored online.

Due to its low alkalinity, NEWater is conveyed to non-domestic customers and reservoir injection points in pipes that are lined with high density polyethylene. The pipeline network includes a system of service reservoirs which further increases the response retention time. Subsequently, NEWater is stabilized with lime allowing other pipes, like cement lined ductile iron pipes, to be used.

CS4.3.4 Environmental buffer and blending

NEWater is channelled into reservoirs where it is mixed with rainwater and undergoes further treatment at a water works before being supplied to households. The reservoir serves as an environmental buffer, providing a long retention time through its large volume, and allowing for natural attenuation.

CS4.4 Water quality monitoring: Ensuring the quality of NEWater

The system of multiple barriers is complemented by strict operational control and a comprehensive water quality monitoring programme to ensure that NEWater meets quality standards at all times. This is verified during regular quality audits.

CS4.4.1 Operational control

Operational control based on real-time water quality data is critical to safeguarding NEWater quality. Continuous online monitoring is achieved with the use of surrogate parameters, which are indicative of water quality and treatment efficacy. Plant operators monitor the trends of these parameters and take appropriate actions to maintain water quality close to the baseline performance of the plant, which is more stringent than drinking-water standards. Table CS4.2 shows the parameters that are typically monitored online at various points in the treatment process.

Table CS4.2 Parameters for operational control in NEWater plant

Location	Parameter	Indication
Water reclamation plant	Total organic carbon	Source water contamination
	Conductivity	
	Ammonia	Effectiveness and stability of WRP processes
	Turbidity	
	Total chlorine	Control of chloramination for membrane fouling control
	Oxidation reduction potential/free chlorine	
Reverse osmosis permeate/product water tank	Total organic carbon	Source water contamination
	Conductivity	Breach in RO Integrity
	Total chlorine	Residual chlorine before distribution

Online monitoring of ammonia and turbidity levels in the treated wastewater offers a good indication of the conditions of the WRP treatment processes and quality of feed-stock to the NEWater plant. Total chlorine is monitored at various points along the treatment train to assess the effectiveness of chloramination in controlling membrane biofouling. Total chlorine in the product water is also monitored to ensure that a consistent level of residual chlorine is present in NEWater before distribution for IPR and direct non-potable use.

Total organic carbon is critically monitored, as it is sensitive to any breach in RO membrane integrity and source water contamination by VOCs. This is measured from the RO permeate and after the product water storage tank. The TOC in NEWater is typically below 100 µg/L. The operators promptly investigate any rapid increase in the TOC trend as it could indicate source water contamination. It is thus an effective surrogate parameter to ensure that NEWater meets drinking-water standards, which is verified after laboratory testing. Laboratory testing is useful for verification but not for operational control as analysis requires time (up to a month for some parameters).

Conductivity is the other critical online parameter used for operational control as it is indicative of the TDS in the treated wastewater and product water. If unusually high conductivity is detected in the treated wastewater, the RO permeate can be recycled back to the RO feed tank to dilute the feedwater and maintain the quality of the product water. Conductivity is also measured before and after the RO system to determine the membrane salt rejection rate, which is a useful indicator of membrane effectiveness in removing contaminants. A sudden increase in conductivity may indicate a drop in salt rejection, suggesting that the RO membranes could have been damaged and require immediate replacement. A gradual drop in salt rejection over time is indicative of membrane ageing. Scheduled replacement of membranes is carried out.

To verify the accuracy of online instruments, operators collect water samples and perform laboratory analysis once every eight-hour shift, three times daily. Instruments are serviced if there are significant deviations (more than 5%) between the laboratory results and online readings.

CS4.4.2 Water quality monitoring programme

In addition to online quality parameters, a comprehensive sampling and monitoring programme is in place to track NEWater quality over time and ensure its suitability for IPR. The programme covers various sampling points in the entire water supply chain and is reviewed and updated regularly to keep track of new findings on CECs. To date, more than 330 physical, microbial, chemical and radiological parameters are monitored under the sampling and monitoring programme. The trends of the various parameters measured are monitored closely and deviations from baselines are investigated and rectified.

Over the past 16 years, more than 140 000 tests have been conducted on NEWater by PUB's International Organization for Standardization/International Electrotechnical Commission 17025 accredited laboratory and all the test results are well within the respective drinking-water guidelines/standards established by Singapore's National Environment Agency, USEPA and WHO. Some examples of the parameters tested are shown in Annex CS4.1.

Both the water quality data from laboratory tests and online monitoring are aggregated in an integrated water management system equipped with six-sigma process improvement tools and a web-based interface to facilitate analysis and reporting. The system alerts operators and managers if water quality deviates significantly from baseline performance.

CS4.4.3 Surveillance and audit

The National Environment Agency (2008) regulates drinking-water quality in Singapore according to its Environmental Public Health (Quality of Piped Drinking-water) Regulations 2008. In addition, NEWater quality is benchmarked against the following standards:

- PUB internal operational control limits;
- USEPA (2014) National Primary Drinking-water Regulations; and
- WHO Guidelines for Drinking-water Quality (WHO, 2017a).

Water quality data, operation and maintenance of plants and staff competence are audited by an internal audit panel and an independent external audit panel. Each panel convenes twice yearly. The internal audit panel focuses on operational details such as water quality data integrity, adherence to standard operating procedures and maintenance schedules and plant staffing needs. The external audit panel comprises local and overseas experts. It examines the overall sampling and monitoring programme, plant operations and major new projects, and recommends improvements after considering best practices and emerging concerns for drinking-water.

CS4.5 Incident management

In the event that the NEWater produced does not meet required quality specifications, the incident management approach is built on the main objectives to:

- safeguard the quality of water in the product water storage tank;
- restore production; and
- investigate and eliminate source of contamination.

For example, in the event of a continuous rise in TOC trend, the critical steps involved are as follows:

- reverse osmosis permeate sent to waste stream while monitoring TOC trend. Plant shut down if rising trend persist;
- water samples collected for laboratory analysis to identify contaminant;
- source control team investigates likely dischargers;
- feed tanks drained down and replenished with fresh treated wastewater; and
- NEWater production restored when TOC level subsides.

The NEWater plant operators and source control teams work closely to restore NEWater quality, usually within several hours. The PUB management is kept informed at critical junctures (e.g. plant shut down, restoration of supply).

CS4.6 Public outreach and stakeholder engagement: Building confidence

Besides having a robust system in place to ensure the quality of NEWater, public confidence in NEWater for IPR was essential for its implementation to be successful. Learning from the experience of other utilities, Singapore set out to design a comprehensive education and engagement programme that would gain public trust and acceptance. It was open and transparent in addressing all the possible health, safety and quality concerns. As part of public outreach a NEWater Visitor Centre integrated with the treatment plant was established in 2004. Public outreach is discussed in further detail in Appendix A4.1.

Singapore's NEWater Visitor Centre (source: PUB, Singapore).

CS4.6.1 Assessment and technology demonstration of water safety before implementation

The two-year Singapore water reclamation study (NEWater study) (Section CS4.2), with a 10 000 m^3/day (10 MLD) demonstration plant, allowed the PUB to assess the water reuse technology in Singapore's environment and fine tune its application. The quality of NEWater produced was comprehensively tested and monitored for compliance with drinking-water standards. Under the Health Effects Testing Programme, NEWater was tested for short- and long-term toxic and carcinogenic effects on mice and fish, as well as estrogenic effects on fish, and found to have no effect (Tan et al, 2008). The assessments were carried out in collaboration with the National Toxicology Programme and Experimental Pathology Laboratories in the USA. The results were evaluated by an independent panel of experts, which concluded that NEWater was safe for potable use. This gave the study greater credibility and provided a solid foundation on which to build the public education and engagement programme.

CS4.7 Conclusions

Over the past 16 years, NEWater has grown from a demonstration-scale project to a sustainable water source able to meet 40% of Singapore's water needs today and projected to meet up to 55% of water needs by 2060 (PUB, 2016). It has helped Singapore to overcome its land constraints for catchment and storage, and increased its resilience against climate change. IPR has been successfully practised since 2003 and public confidence in NEWater quality remains high owing to continual public engagement and a strong track record of reliable and constantly high-quality water supply. This can be attributed not only to a good technical solution, but more importantly to sound governance, strict operating procedures executed by technically competent, well trained and experienced operators, a comprehensive water quality monitoring programme, and a system of independent audits to offer further assurance.

Annex CS4.1 Quality of NEWater

Table ACS4.1 Quality of NEWater since year 2000 (selected parameters)

	Unit	Detection limits	Value
Physical parameter controls			
Total organic carbon	µg/L	20	40–100
Suspended solids	mg/L	2.5	<2.5
Turbidity	NTU	0.1	<0.1
Trace contaminants			
Total estrogen	µg/L	0.003	<0.003
Estrone	µg/L	0.001	<0.001
17β-Estradiol	µg/L	0.001	<0.001
Ethinyl estradiol	µg/L	0.001	<0.001
Ibuprofen	µg/L	0.005	<0.005
Naproxen	µg/L	0.005	<0.005
Gemfibrozil	µg/L	0.005	<0.005
N-Nitrosodimethylamine	ng/L	2	<2–10
1,4-Dioxane	µg/L	1	<1
Methyl tertiary butyl ether	µg/L	5	<5
Polychlorinated biphenyls	µg/L	0.2	<0.2

CS5 Perth, Australia, groundwater replenishment

CS5.1 Overview and background

The city of Perth has been experiencing the effects of a drying climate with significantly reduced rainfall. Current average rainfall is 840 mm, with an average rainfall decline of over 30% since the early 1990s. This has had a significant impact on stream flows, as well as surface and groundwater reserves. A 12% decline in rainfall since 1990 has resulted in a 50% reduction in stream flows into Perth's reservoirs. The situation has resulted in a review of the long-term feasibility of traditional drinking-water sources; a detailed research into water usage; investigations into additional groundwater reserves; and consideration of alternative supply options, including the first major desalination plant completed in 2006 and IPR through GWR. The Water Corporation, the major drinking-water provider in Western Australia, has developed a multiple portfolio of options to drought-proof Perth through its "Water forever" planning process (Water Corporation, 2009).

In 2004, the Water Corporation identified GWR as a potential water source for Perth and in 2005 the Environmental Protection Authority provided strategic advice on GWR recommending that a trial be undertaken in an area of low risk to human health and the environment (EPA, 2005). Based on this advice, the Water Corporation performed a three-year feasibility study and subsequently commenced a three-year GWR trial at its Beenyup WWTP site at Craigie, in Perth's northern suburbs.

Groundwater replenishment is an integral component of the Water Corporation's 50-year plan to secure water supplies for Perth (Water Corporation, 2009). The aim of GWR is to enhance secondary treatment of wastewater with advanced processes to produce recycled water which meets Australian Drinking Water Guidelines (NHMRC-NRMMC, 2011) prior to being recharged to an aquifer for storage and later use as a drinking-water source.

A three-year feasibility study (2005–2008) was conducted to determine the viability of augmenting drinking-water supplies through GWR using membrane filtration treatment (MF and RO). A research project "Characterising treated wastewater for drinking purposes following reverse osmosis treatment" was led by the Department of Health in partnership with regulatory agencies, universities and industry (Buynder et al, 2009). During the study period, secondary wastewater from the three largest Perth metropolitan WWTPs (Beenyup, Subiaco and Woodman Point) and recycled water from two advanced WWTPs were analysed (namely, Kwinana water reclamation plant and Beenyup pilot plant).

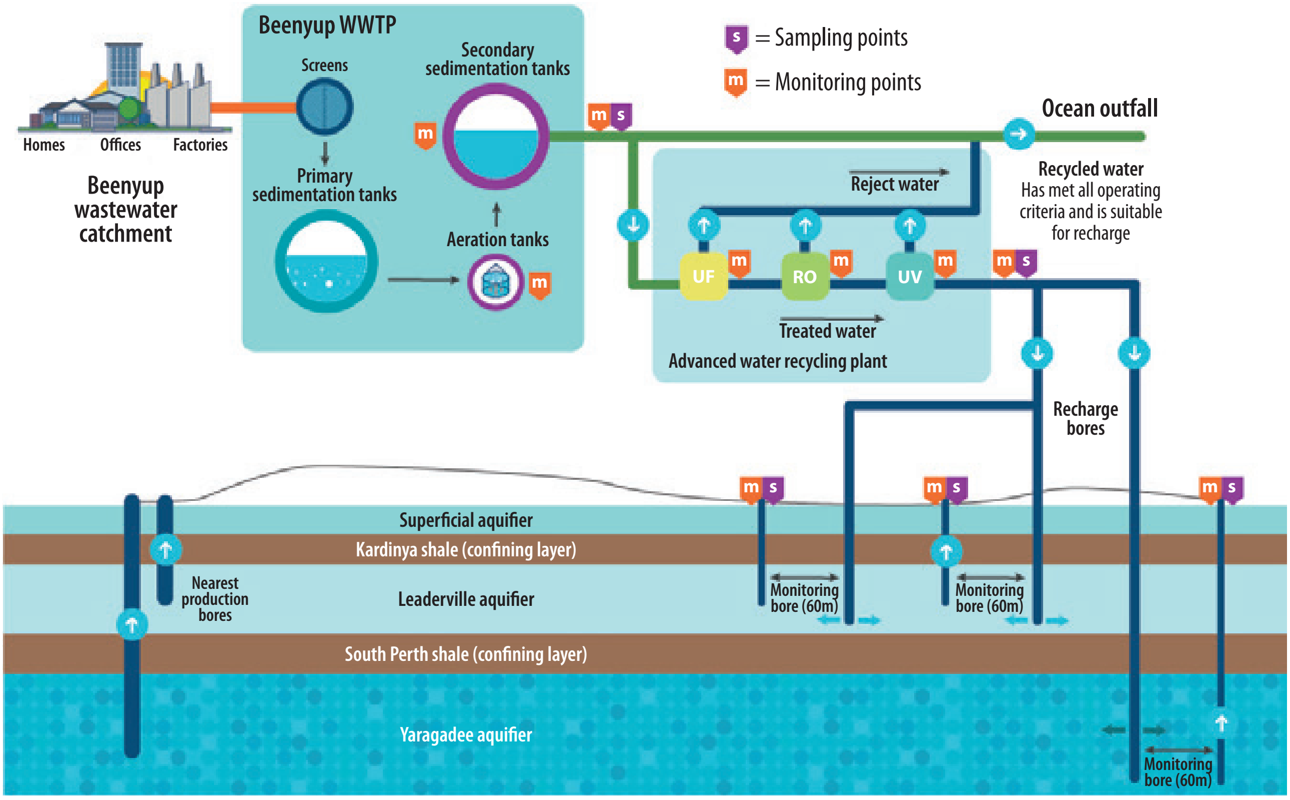
The feasibility study demonstrated that the advanced treatment using MF and RO was adequate to protect public health and the study provided valuable information for the selection of pathogen and chemical indicators for monitoring the GWR scheme (see Section CS5.4).

After completion of the feasibility study, a three-year GWR trial (2010–2012) was conducted. The trial involved an advanced water recycling plant (AWRP), further treating up to 5 MLD of secondary-treated wastewater from the Beenyup WWTP using UF, RO and UV disinfection. The water was then recharged into the confined Leederville aquifer at a depth of 120 to 220 m. During the trial, a total of 2533 ML of recycled water was recharged. Water quality was monitored throughout the treatment process and via 22 groundwater monitoring bores located at the Beenyup site (Water Corporation, 2013).

After successful completion of the trial, construction for the full-scale GWR scheme started in October 2014 and commenced operation in 2016. The full-scale plant will initially be able to recharge 14 GL/year with capacity to be expanded to 28 GL/year. On average, Perth uses about 270 billion L of potable water a year and up to 20% of Perth's drinking-water needs could be supplied by GWR by 2060.

The scheme is owned and operated by the Water Corporation of Western Australia, a publicly owned water utility. The estimated cost of the full-scale GWR is Australian $ 124.6 million.

Figure CS5.1 Groundwater replenishment scheme design (not to scale)



Source: Water Corporation, Western Australia, Australia.

CS5.2 Approach: Establishment of potable reuse scheme

The scheme will accept wastewater from the Beenyup wastewater catchment in the northern suburbs of Perth with a total inflow of approximately 135 MLD. The majority of wastewater collected in the wastewater catchment is sourced from households. Trade waste and process wastewater from industrial and commercial customers represents approximately 2.4% by volume of the wastewater flow. By load, trade waste represents about 20% of biochemical oxygen demand, 5% of suspended solids, 25% of oil and grease, 3% of nitrogen, 2% of phosphorus and 3% of dissolved salts. The largest industrial and commercial customers are food producers and laundries, but most trade waste is from small commercial businesses. There are three significant hospitals and a number of smaller facilities that discharge wastewater into the catchment. The medical facilities' wastewater undergoes pre-treatment where appropriate and substances incompatible with the Beenyup system are not accepted.

A comprehensive characterization of the secondary-treated wastewater completed during the feasibility study included testing for almost 400 chemicals, including pesticides, metals, pharmaceuticals, industrial chemicals, endocrine disruptors and persistent organic pollutants, such as dioxins, furans and PCBs among others. The majority of chemicals analysed were detected in the secondary wastewater, with some chemical groups, including metals, DBPs and polycyclic aromatic hydrocarbons, detected at concentrations above health-based values. Concentrations of radioactive material at the Beenyup WWTP secondary wastewater were below the Australian Drinking Water Guidelines screening levels of gross alpha and beta radioactivity while microbiological parameters tested (*E. coli*, enterococci, coliphages and adenoviruses) were always detectable. Advanced treatment using UF and RO was able to reduce microbial and chemicals constituents to levels below health significance.

The scheme will be managed through a risk management plan (equivalent to a WSP) as described in the Australian Guidelines for Water Recycling (NRMMC-EPHC-NHMRC, 2006–2009). The 12 elements of the wastewater quality framework cover fundamental issues such as system identification, risk assessment, operational procedures, maintenance, monitoring, and incident and emergency management, and extend to formalizing supporting requirements such as policy development, employee training, community involvement and research and development.

CS5.3 Control measures

The treatment systems for the GWR scheme will include the Beenyup WWTP, the AWRP and four recharge bores which recharge approximately 45 MLD of recycled water into the Leederville and Yarragadee aquifers. Groundwater will then be abstracted and treated before distribution through the Perth Integrated Water Distribution System.

Multiple treatment processes are used in series to minimize the impact that failure or poor performance of a single treatment process has on the overall ability to meet health and environmental water quality requirements.

The GWR scheme utilizes the following preventative measures to produce recycled water (Figure CS5.1):

- wastewater catchment management;
- Beenyup WWTP (primary and secondary treatment);
- advanced water recycling plant (UF, RO, UV treatment);
- storage (storage/buffer tank); and
- aquifer storage.

CS5.3.1 Wastewater catchment management

The proportion of trade waste in the inflow to the Beenyup WWTP is low. However, the following process and procedures are implemented to mitigate any potential risk in the wastewater catchment:

- **Specification of trade waste acceptance criteria:** The trade waste acceptance criteria specify the wastewater quality that is allowed into the sewerage system. The criteria preclude amounts of substances which might interfere with wastewater collection, treatment, reuse or discharge to the environment. The acceptance criteria include alarm limits for loading of substances (by mass), including biochemical oxygen demand, suspended solids and nutrients.
- **Permitting (or registering) of commercial and industrial waste customers:** All businesses require a permit to discharge trade waste to allow discharge into the sewerage system. The wastewater from each business is characterized and risks assessed against the end-points relevant to the catchment. Permits specify the allowable waste that may be discharged and conditions of discharge, such as pre-treatment and reporting requirements.
- **Response plans for large customers:** Permits of large customers or high-risk customers contain requirements for real-time notification to the Water Corporation (commercial and industrial services) of process or pre-treatment failures which may impact on the quality of the wastewater that is being discharged.
- **Surveillance monitoring of customers with high load discharges or potential quality concern:** These customers are subject to ongoing surveillance programmes, which involve unannounced compliance inspections, and a programme to characterize loadings using automatic samplers to collect flow-weighted composite samples. The frequency of compliance inspections is determined from a risk ranking model which considers the size and nature of each business and the type of pre-treatment used. The frequency of composite sampling is determined by the size and variability of the loading. Loadings from some large customers are determined via self-monitoring to Water Corporation protocols.
- **Response plans for unusual discharges:** A procedure exists for responses to unusual discharges recorded in the wastewater collection system or at WWTPs.

CS5.3.2 Beenyup WWTP

The Beenyup secondary WWTP incorporates the following treatment steps:

- screens and grit removal;
- primary sedimentation; and
- secondary treatment incorporating biological nutrients via pipeline to an ocean outfall. Part of the discharge from the plant (approximately 67 MLD) is supplied as feedwater for the AWRP.

CS5.3.3 Advanced water recycling plant

The AWRP will accept flows from the Beenyup WWTP and then treat the water as follows:

- turbidity monitoring and ammonia. High turbidity flows are diverted from the AWRP to the ocean outfall;
- coarse screens to protect the AWRP treatment processes;

- 2.8 ML storage tanks (one-hour storage) to allow for continued operation of the AWRP should turbidity or ammonia of feedwater exceed acceptance criteria for short periods;
- dosing with preformed monochloramine;
- fine strainers remove particles;
- microfiltration;
- reverse osmosis (25% of flow-reject water is discharged through the ocean outfall);
- ultraviolet disinfection;
- sodium hydroxide dosing to increase the pH;
- 1 ML storage tank to buffer flows (three-hour storage) before recharge; and
- recharge bore network to pump recycled water into the Leederville and Yarragadee aquifers (45 MLD).

The benefit of GWR is that the aquifer provides a significant buffer between the recycled water and its future use as a drinking-water source. Water is treated to drinking-water standards as required by the health regulators before injection into the Leederville and/or Yarragadee aquifers to prevent contamination of Perth's groundwater drinking-water source.

To ensure that adequate treatment is provided, the Department of Health requires a minimum treatment performance to meet log reductions specified in the Australian Guidelines for Water Recycling (NRMMC-EPHC-NHMRC, 2006–2009):
- 8.1 log for *Campylobacter* (bacteria);
- 9.5 log for adenovirus and rotavirus combination (enteric viruses); and
- 8 log for *Cryptosporidium* (protozoa and helminths).

The full treatment train and the equivalent log reduction credits for both the Beenyup WWTP and the AWRP are presented in Table CS5.1

Table CS5.1 Treatment barriers and equivalent log reduction credits

Treatment barrier	Equivalent log reduction credits		
	Bacteria	Adenovirus	Protozoa
Secondary treatment	1.0	1.0	0.5
Membrane (ultra) filtration	3.0	3.0	3.0
Reverse osmosis	3.0	3.0	3.0
Ultraviolet disinfection	4.0	3.0	4.0
Total log reduction credit	**11.0**	**10.0**	**10.5**
Required log reduction	**8.5**	**9.5**	**8.0**

CS5.4 Water quality monitoring

Monitoring of the scheme is based on operational and verification monitoring. Operational monitoring is used to determine if each preventative measure is effectively controlling hazards, and provides advance warning if treatment barriers are moving away from a stable operational state. Online parameters for the Beenyup AWRP are presented in Table CS5.2.

Operational monitoring of the AWRP includes:
- Continuous online monitoring of the CCPs and many process control points. Any breach of an alert limit will produce an alarm to notify operators that manual intervention may be required or that an automated response has occurred. Breach of a violation limit will trigger an automatic diversion of recycled water or a shutdown of the AWRP to ensure that non-compliant water does not proceed to the next treatment barrier or is not recharged into the Leederville and/or Yarragadee aquifers.
- Observational monitoring undertaken by the GWR process coordinators to check systems prior to taking corrective actions or a routine check of systems.

Table CS5.2 Beenyup advanced water recycling plant process control points and critical control points

Process	Parameter	Critical control point
Feedwater **Inlet works**	Turbidity	Yes
	Ammonia	Yes
	Conductivity	No
	pH	No
	Oxidation reduction potential	No
Ultrafiltration (each skid)	Pressure decay test	Yes
	Turbidity	Yes
Ultrafiltration combined filtrate	Combined turbidity	Yes
	Monochloramine	No
	Free ammonia	No
Ultrafiltration clean in place	pH	No
	Oxidation reduction potential	No
	Temperature	No
Reverse osmosis feed	Chloramine	No
	Free ammonia	No
	Total chlorine	No
	Total organic carbon	No
	pH	No
	Oxidation reduction potential	No
Reverse osmosis trains	Conductivity	No
Reverse osmosis trains combined permeate	Conductivity	Yes
	Free ammonia	No
	pH	No
	TOC	Yes
Ultraviolet feedwater	UV transmittance	Yes
	UV flow	Yes
	Validated UV dose	Yes
Recycled water	pH	Yes
	Chloramine	No
	Conductivity	No

In addition to operational monitoring, verification monitoring through laboratory analysis is used to confirm that the treated water quality is consistently achieving compliance with the Department of Health recycled water quality parameters.

During the feasibility study a subset of 18 recycled water quality indicators were identified to demonstrate likely compliance with the much larger set of 292 water quality parameters measured to verify drinking-water quality (Table CS5.3). The indicators were chosen to:

- have characteristics linked to a predominant removal mechanism (e.g. filtration, adsorption or oxidation);
- be present in concentrations representative of a broader class of compounds and that are sufficiently high to determine a meaningful degree of reduction through a unit process or a sequence of processes; and
- be quantifiable using an established, and preferably accredited, analytical method.

Table CS5.3 Recycled water quality indicators for groundwater replenishment in the Beenyup wastewater catchment

Parameter	Unit	Guideline value	Limit of reporting	Chemical group represented
Boron	mg/L	4	0.02	Inorganic chemicals
***N*-Nitrosodimethylamine**	ng/L	100	1	Nitrosamines
Nitrate as nitrogen	mg/L	11	0.01	Inorganic chemicals
Chlorate	mg/L	0.7	0.01	Inorganic DBPs
1,4-Dioxane	µg/L	50	0.1	Organic chemicals
Chloroform	µg/L	200	0.05	Other DBPs
Fluorene	µg/L	140	0.1	Organic chemicals
1,4-Dichlorobenzene	µg/L	40	0.05	Organic chemicals
2,4,6-Trichlorophenol	µg/L	20	1	Phenols
Carbamazepine	µg/L	100	0.05	Pharmaceuticals and personal care products
Estrone	ng/L	30	1	Hormones
Ethylenediaminetetraacetic acid	µg/L	250	10	Organic chemicals
Trifluralin	ng/L	50 000	1	Pesticides and herbicides
Diclofenac	µg/L	1.8	0.05	Pharmaceuticals and personal care products
Octadioxin	pg/L	9000	2	Organic chemicals
MS2 coliphage	pfu/L	<1	0.6	Microorganisms/pathogens
Alpha particle activity	mBq/L	500	10	Radioactive compounds
Beta particle activity (-K40)	mBq/L	500	10	Radioactive compounds

Note: Sampled results should be equal to or less than the guideline value.

The key physico-chemical properties that determine chemical rejection by MF/RO are size (molecular weight, width and length), hydrophobicity (log K_{ow}, log D), and acidic/basic character (pKa). Log K_{ow} also provides information on polarity (dipole moment) and solubility in water (associated with chemical charge). The recycled water quality indicators include chemical groups with different:

- molecular weights (ranged from 10.8 to 296 g/mol);
- hydrophobicity properties (log K_{ow} ranged from -0.64 to 3.4); and
- acidic/basic characteristics (pKa ranged from 2.13 to 10.4).

Some of the indicator parameters were not consistently found in the secondary wastewater during the monitoring programme but allow demonstration of the safety of the treated water with respect to specific chemical groups, and provide additional confidence that all chemical hazards are being mitigated. MS2 coliphage was selected as the key microbial indicator to be used to measure the effectiveness of the advanced water treatment plant to remove microorganisms.

The indicator parameters are monitored at a higher frequency than the full set of recycled water quality parameters.

CS5.4.1 Audits

A review of the effectiveness of the risk management plan for the GWR trial was undertaken annually by the Water Corporation. The results demonstrated >90% compliance with the requirements of the Australian Guidelines for Water Recycling risk management plan framework. An external audit by Deloitte Touche Tohmatsu concluded that the systems and processes used to manage the GWR trial were suitable to deliver a safe, reliable and sustainable drinking-water source option that adequately protects human health and the environment (Water Corporation, 2013).

CS5.5 Incident management

Any recycled water quality event as defined by the memorandum of understanding will trigger an incident as defined in the GWR incident and emergency management plan. Any serious water quality event requires notification to the Department of Health within 24 hours.

The Department of Environment Regulation licence requires the Water Corporation to notify the Department of Environment Regulation within 24 hours if sample results indicate that recycled water exceeds a limit specified in the GWR discharge licence.

For the GWR trial, the treatment process operated within CCP limits 99.93% of the time. There were three instances where the CCPs did not meet specifications whilst recharge continued. These events did not pose a risk to the environment or human health.

CS5.6 Public outreach

During the feasibility study and before commencement of the GWR trial numerous activities were undertaken to consult and engage key stakeholders, including community groups. Stakeholder engagement has continued throughout implementation of the GWR scheme working with key stakeholders and influencers of opinion to build credibility and trust (and therefore third-party advocacy) and engaging with the broader community.

The community and stakeholder engagement strategy employed a two-step communication theory of informing opinion leaders first and then continuing to inform the broader community. In order to build trust, the strategy was primarily based on a face-to-face approach, rather than relying solely on mass communication methods. These activities were supported by advertising, media relations, social media communication channels and other traditional public relations tools where appropriate. A community advisory panel, representing various sectors of the community including public health, environment, business and the interests of local residents, met regularly throughout the trial and they provided independent advice regarding operations and community sentiment on GWR. In addition, a trial website page was created, including regular water quality reports, and more than 11 000 people toured the plant site and visitor centre.

Presentations and briefings to over 160 health, environment and local government stakeholder groups, including local councils and other decision-making authorities, local Aboriginal groups and community groups, occurred throughout the GWR trial.

The GWR trial was positively received and publicly supported by all political groups with community support for GWR remaining steady at between 70 and 76%.

By proactively engaging with stakeholders, the Water Corporation has been able to address any concerns, perceptions or possible misconceptions about GWR. This approach has proven successful in minimizing time spent on reactive methods to correct misinformation about GWR and reinstate trust. During the GWR trial, a stakeholder database was developed and this will continue to be used during implementation of the GWR scheme.

CS5.7 Governance

The following regulatory authorities are key stakeholders in providing the regulatory and formal requirements of the GRW scheme:

- Department of Water
- Department of Health
- Department of Environment Regulation
- Environmental Protection Authority.

An interagency agreement between the Water Corporation and these regulatory agencies was executed in March 2007 to develop policy and regulation for GWR and assess its feasibility as a sustainable water source.

An interagency working group was established to progress regulatory requirements. The working group developed the trial's regulatory framework, which defined the requirements for the ongoing regulation of GWR, using existing statutory processes where possible, and following national guidelines to assess unique aspects (IAWG, 2008). Among gaps identified, the minimum distance between the recharge zone and abstraction for drinking (known as the recharge management zones) was later defined as 250 m for future GWR schemes at the Beenyup site. The GWR regulatory framework was signed by all agencies in December 2012.

A memorandum of understanding between the Department of Health and the Water Corporation for the GWR trial was established in July 2010, which formalized the relationship between the parties for the GWR trial (Department of Health & Water Corporation, 2010). This describes the regulatory approval and operational requirements of the GWR trial, including water quality and reporting requirements, notification of water quality events and communications protocols.

CS5.8 Conclusions, challenges and lessons learned

The GWR as a rainfall independent source of water for Perth has proven to be successful. A key aspect to the successful implementation of the project was the early engagement of the community and the clear communications between government, industry and the community to achieve a sustainable outcome for the management of the Western Australia water resources.

CS6 Direct potable water reuse in Texas, United States of America

CS6.1 Overview and background

The Permian Basin, like much of the western United States, has been subjected to an unprecedented period of drought. While rains have recently provided some relief from the current drought in Texas, reservoir levels remain low in the basin; and some reservoir yields have been shown to have declined. As a result, drinking-water providers have needed to consider new water supply sources.

A summary is provided of two utilities that are looking to potable water reuse to augment their supplies.

CS6.2 Approach

As part of its mission statement "to protect our state's public health and natural resources consistent with economic development", the Texas Commission on Environmental Quality regulates public health and the environment in Texas, including all aspects of wastewater treatment and disposal, and water supply and treatment. Faced with an urgent need for additional water supplies in many parts of the state, the commission has been approving DPR projects on a case-by-case basis in accordance with an innovative/alternative treatment clause in state regulations (30 TAC 290) that allows "any treatment process that does not have specific design requirements" listed in that chapter to still be permitted on the basis of a case-by-case review. The commission regulates DPR as a special type of raw water source mainly under existing drinking-water regulations. This means water from DPR projects must meet all existing drinking-water quality requirements such as USEPA maximum contaminant levels. The Texas Commission on Environmental Quality also encourages monitoring for unregulated constituents such as pharmaceuticals and personal care products.

Consistent with the starting point taken by others in determining regulatory requirements for potable reuse (CDPH, 2014; Trussell et al, 2013), the commission requires that DPR systems demonstrate that they will achieve finished water quality goals for enteric virus (2.2×10^{-7} MPN/L), *Giardia* (6.8×10^{-6} cysts/L) and *Cryptosporidium* (3.0×10^{-5} oocysts/L) (Table CS6.1) (TWDB, 2015). The justification for these numbers is based upon meeting the 1 in 10 000 per capita risk of infection (USEPA, 2006b; Regli et al, 1991), which is the governing paradigm underlying the Surface Water Treatment Rule and its relevant amendments (USEPA, 2010).

Table CS6.1 Pathogen concentrations in finished water corresponding to a 1 in 10 000 annual risk of infection

Pathogen	Concentration	Reference
Viruses[a]	2.2×10^{-7}/L	Regli et al (1991)
Giardia	6.8×10^{-6} cysts/L	Regli et al (1991)
Cryptosporidium	3×10^{-5} oocysts/L	Haas et al (1996)
Total coliforms[b]	1 CFU/L	Trussell et al (2013)

[a] Acceptable concentration depends strongly on the virus selected, with rotavirus showing the lowest concentration of the viruses examined (2.2×10^{-7}/L).
[b] Bacterial removal requirements based on *Salmonella enterica* which require 9-log reduction to achieve 10^{-5} risk level. Total coliform used as an indicator in place of *S. enterica* with assumption that 9-log reduction would reduce levels from 10^{9} CFU/L to 10^{0} (1) CFU/L.

These finished water pathogen concentrations are too small to be directly measurable, so the LRV concept is applied to DPR the same way it is applied under existing surface water treatment regulations. A similar approach has been adopted by others (CDPH, 2014; Trussell et al, 2013). One difference adopted by the commission is that the starting point for LRV treatment requirements is treated wastewater rather than raw wastewater. The baseline targets adopted (Table CS6.2) are used in conjunction with a case-by-case evaluation of the pathogen loads in the specific wastewater that is to be used for DPR to determine required LRVs (TWDB, 2015). This means that each DPR project in Texas is assigned individualized treatment requirements and that these might change over time if warranted by ongoing monitoring programmes. This regulatory approach has allowed the commission to adapt its approach to a number of different scenarios that have been proposed by utilities across the state.

Table CS6.2 Baseline pathogen log reduction targets for direct potable reuse

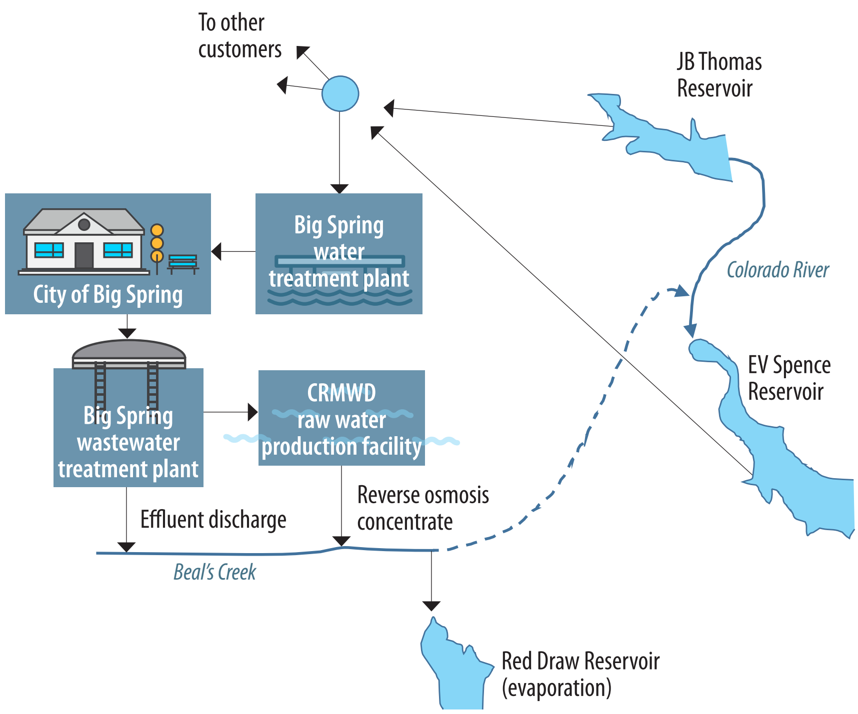
	Pathogens		
	Viruses	*Cryptosporidium*	*Giardia*
Log reduction	8	5.5	6

CS6.3 The Colorado River Municipal Water District

The Colorado River Municipal Water District (CRMWD) supplies water to its member cities of Big Spring, Snyder and Odessa, as well as several customer cities, including Midland, San Angelo and Abilene. Most of the water supplied is raw surface water from the three reservoirs that CRMWD has constructed on the Colorado River: JB Thomas, EV Spence and OH Ivie. These sources are supplemented by groundwater reserves in the western portion of the CRMWD service area, but additional supplies are expected to be needed to meet growing needs and to offset apparent losses in reservoir yields.

The district continues seeking new supplies and alternatives to continue providing a water supply to its member and customer cities. A source of supplementary supply originates from the treated wastewater currently discharged by cities in the CRMWD service area. This new supply and connection to the system is shown in Figure CS6.1.

Figure CS6.1 Colorado River Municipal Water District raw water production facility



The DPR project in Big Spring supplements the raw groundwater and surface water sources for up to five other public water systems by introducing a purified treated wastewater as alternate raw source water. The advanced treatment plant is known as the raw water production facility as it is creating a source with the same or better water quality than the natural surface water. The water from the reclamation facility is blended with raw surface water and then treated further in conventional drinking-water treatment plants before it is delivered to customers. The raw water production facility is permitted to provide up to 50% of the raw water piped to the various water treatment plants. The facility has been producing water since spring 2013.

This potable water reuse application is characterized as DPR, as there is no environmental buffer (surface water reservoir or groundwater basin) that provides an extended amount of time between the treatment of the water and the use of the water.

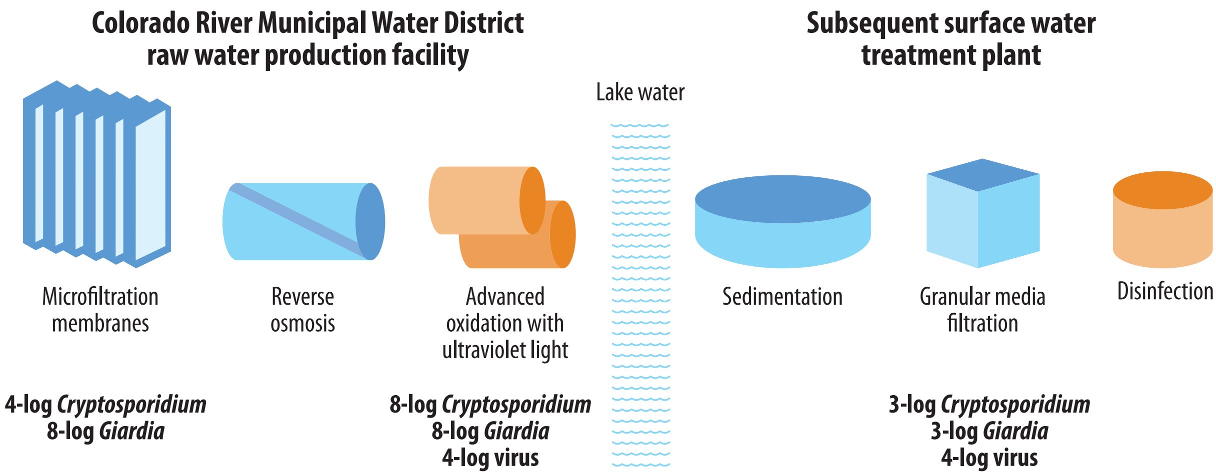
CS6.3.1 Control measures: Treatment processes

The raw water production facility takes the treated wastewater from the city of Big Spring WWTP, treats it with MF membranes, RO and AOP (UV/H_2O_2) before the product water is discharged into the raw water pipeline.

The Texas Commission on Environmental Quality assigned the log reduction values for each unit process based on the methodology used for drinking-water facilities prescribed in the Long Term 2 Enhanced Surface Water Treatment Rule (USEPA 2006a; 2010). Figure CS6.2 shows the treatment credits assigned to each unit for the CRMWD raw water production facility. Expected performance of the listed technologies provides a water quality that meets the pathogen risk levels listed in Table CS6.1.

- **Microfiltration:** The MF supplier has completed the necessary third-party challenge study to show the log reductions of protozoa (*Giardia* and *Cryptosporidium*) that can be achieved. As prescribed in the USEPA Membrane Filtration Guidance Manual (USEPA, 2005), daily testing of the MF membranes, using a pressure decay test is used to validate the integrity of the MF membranes and the LRV credits.
- **Reverse osmosis:** For this project, the RO membranes are not granted any pathogen removal credit.
- **Advanced oxidation process (ultraviolet):** The commission provided 4-log virus credits and 8-log protozoa credits.
- **Downstream water treatment plants:** The downstream surface water treatment plants, based on the USEPA Surface Water Treatment Rule (USEPA 2006a; 2010) must also achieve specified minimum virus and pathogen removal or inactivation levels; with 4-log virus credits and 3-log protozoa credits assigned for this project.

Figure CS6.2 Removal and inactivation credits assigned to the raw water production facility and subsequent treatment by a surface water treatment plant



Source: Texas Commission on Environmental Quality, USA.

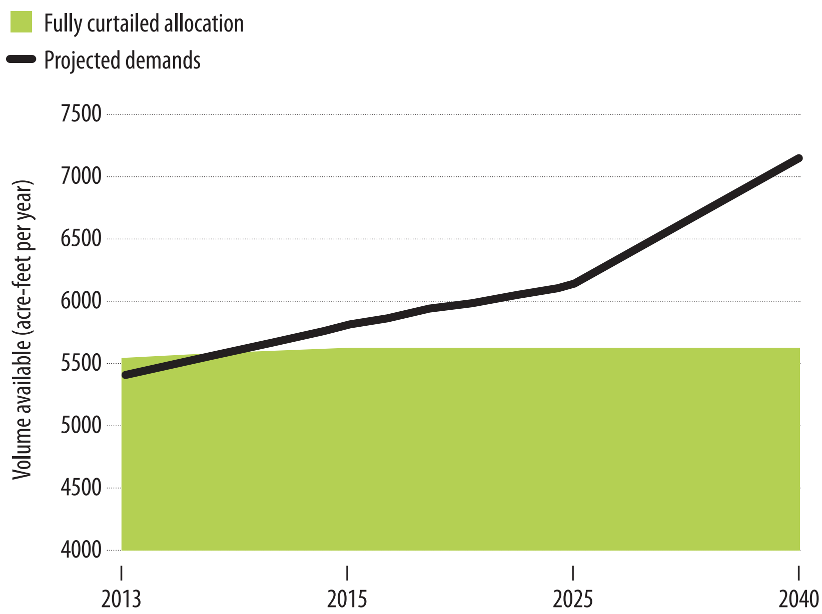
CS6.3.2 Water quality monitoring

The commission requires monitoring of the WWTP effluent, each of the unit process and the finished water of the raw water production facility. The commission set monitoring levels at which actions must be taken, including diverting the WWTP effluent from the entering the facility, turning off specific units or turning off the entire plant. Additionally, the Texas Water Development Board and the WateReuse Research Foundation (WRRF) have funded an extensive analysis of water quality through the facility's treatment processes and a comparative analysis of the existing raw surface water supply. The results from the ongoing study demonstrate that it produces a high-quality water that is protective of public health and easily surpasses the existing raw water quality of the conventional raw surface water with which it is blended (Steinle-Darling et al, 2015).

CS6.4 The Laguna Madre Water District

The Laguna Madre Water District (LMWD) is located in Cameron County, Texas, on the Gulf of Mexico. The district provides water and wastewater services to Port Isabel, South Padre Island, Laguna Heights, Long Island Village and Laguna Vista, and has approximately 6200 customers. The LMWD, like many small communities, has one main water supply source, the Rio Grande; with a water right from the Rio Grande of 7378 acre-feet per year, which is equivalent to 24.9 MLD. This right is subject to curtailment during periods of drought. If the LMWD allotment was fully curtailed, the amount of water that could be withdrawn would be only 5628 acre-feet (19 MLD), representing an increasing water shortage on current and projected demands (Figure CS6.3).

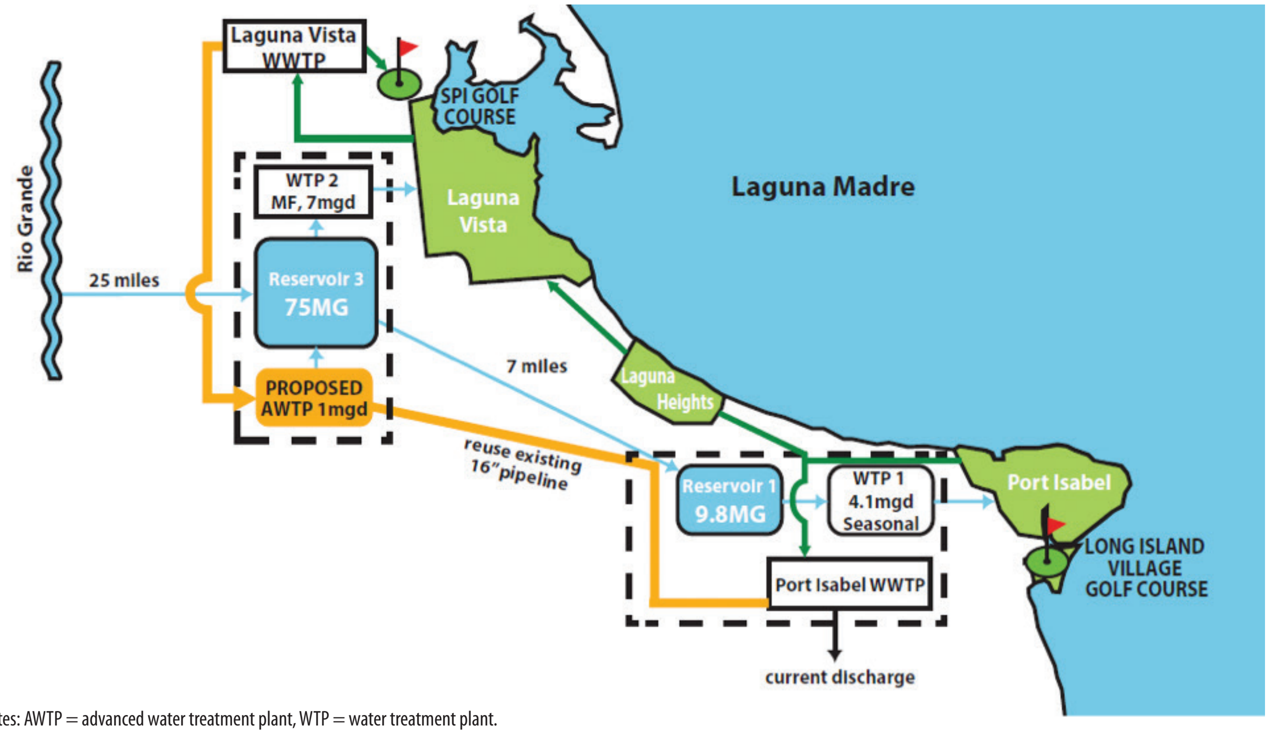
Figure CS6.3 Laguna Madre Water District water demands and drought curtailed allocation, in acre-feet per year



Source: Laguna Madre Water District, USA.

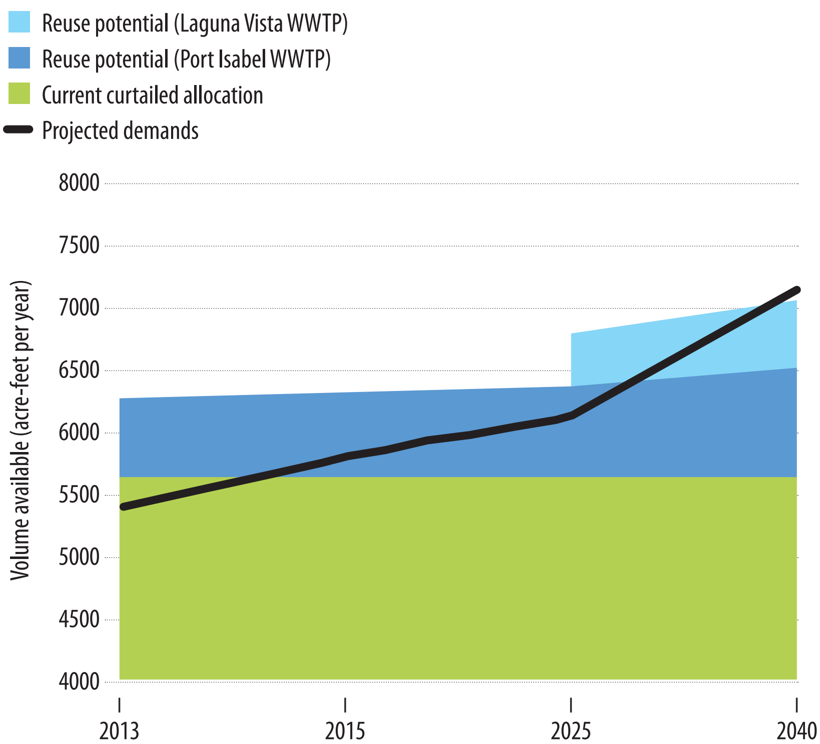
Potable water reuse presents a cost-efficient option to provide a renewable and resilient potable water supply. As part of detailed investigations, the LMWD drafted a plan to capture 1 MGD, equivalent to 3.79 MLD, of treated wastewater from their Port Isabel WWTP, purify the water through advanced treatment, and feed that water to a storage reservoir and then to the LMWD water treatment plant 2, as shown in Figure CS6.4. A second phase will add wastewater from the Laguna Vista WWTP. The benefit of these projects is that the new water will meet projected demands while providing a more reliable water supply with greater drought resilience (Figure CS6.5).

Figure CS6.4 Schematic of potential direct potable water reuse project for Laguna Madre Water District



Notes: AWTP = advanced water treatment plant, WTP = water treatment plant.
Source: Laguna Madre Water District, USA.

Figure CS6.5 Laguna Madre Water District projected water supply with the 0.7 MGD direct potable reuse project (Port Isabel wastewater treatment plant and additional 0.4 MGD expansion (Laguna Vista wastewater treatment plant)



Source: Laguna Madre Water District, USA.

CS6.4.1 Treatment alternatives

The treatment goals for the LMWD were based on the targets identified by NWRI (2013) and using the log reduction value credit approach adopted for CRMWD. The analysis was expanded with an inclusion of CCP-based monitoring and an engineered storage (Salveson et al, 2015). A range of technologies was considered in several configurations, including MF, RO, AOP (UV/H_2O_2), NF and ozone. The treatment performance of these trains is shown in Table CS6.3. Treatment trains 1 and 2 provide the necessary pathogen credits (based on goals from NWRI, 2013), salt removal, reduction of trace pollutants (CECs) and nitrate, as well as all other conventionally regulated chemicals. Treatment train 3 falls short in two areas, *Cryptosporidium* and potentially nitrate.

Table CS6.3 Analysis of pathogen, salt, chemicals of emerging concern and nitrate removal by different potential Laguna Madre Water District treatment trains

Treatment alternative	Pathogen log removal credits				Pollutant removal		
	Bacteria	Virus	*Cryptosporidium*	*Giardia*	Salt	Chemicals of emerging concern	Nitrate
1. MF-RO-AOP (UV/H_2O_2)	15	17	14	14	✓	✓	✓
2. MF-NF-AOP (UV/H_2O_2)	14	16	13	13	✓	✓	✓
3. UF-O_3-BAF-NF-Cl_2	14	16	9	11	✓	✓	?
Goals	**9**	**12**	**10**	**10**			

Notes: BAF = biologically active filtration, Cl_2 = chlorination, O_3 = ozonation, red = (potential) treatment deficiency.

CS6.4.2 Next steps for Laguna Madre Water District

The LMWD is now moving ahead with the design and upgrade of their secondary treatment process, which will provide a high-quality feedwater for future potable reuse. Often improperly seen as a lower priority for potable reuse projects, a high-quality secondary wastewater results in improved overall water quality and reduced operational expenses for advanced treatment systems (NWRI, 2015).

After the secondary upgrades are complete, the LMWD will continue to track the drought and water supply conditions and seek grant funding for a future potable water reuse project.

CS7 Water reuse in South Africa: The eMalahleni water reclamation plant

CS7.1 Overview and background

CS7.1.1 Drivers for potable reuse at eMalahleni, South Africa

South Africa is a semi-arid country and has suffered several severe droughts in the past few decades. The government has a formal plan in place for implementing water reuse, but has yet to apply it on a national or regional level. This has led to opportunities for the private sector to grow in the field of water reuse as well as aiding areas suffering from water shortages.

eMalahleni is an industrial town to the east of the Johannesburg-Pretoria metropole and is surrounded by coal producing mines, steel manufacture and coal-fired power stations. The entire area is known for its numerous mining practices and the adverse effect of AMD on local ground and surface water sources.

Anglo American is one of the mining companies that owns and operates numerous coal mines near eMalahleni. The town has a population of approximately 510 000 people (2012) and receives most of its water from the Witbank Dam, with a capacity of 104 000 ML. At least five mining operations are located in the catchment area, known as the Upper Olifants River Catchment (Naidu, 2012).

The water security of the town was threatened not only by water shortages, but also low water quality due to high amounts of dissolved metals and salts accumulating in the catchment. Anglo American decided to commission a state-of-the-art advanced water treatment plant in order to treat the acid mine water that has been accumulating in the mines, which is estimated to be over 100 GL, similar to the Witbank Dam (Naidu, 2012).

CS7.1.2 History and current status

The original plant, located at the Navigation coal processing plant of Landau colliery, only consisted of a lime neutralization treatment step. The water quality was not well understood at the time, and after only a short period of operation (1994–1995), the plant had to replace almost 70% of the steel piping and other equipment due to the acidity of the water (Gunther & Mey, 2006).

After consulting the Council for Scientific and Industrial Research, the lime neutralization plant was modified and its operation improved, now making use of limestone rather than lime. This resulted in a new challenge in the form of heavy gypsum precipitation and scaling of the coal plant equipment and pipelines.

It was subsequently decided to consider various technologies capable of either metal removal or sulfate removal, or both. After 10 years, several pilot studies were performed of these technologies until the final process configuration was identified.

The first phase of the plant was commissioned in 2007 with a capacity of 20 MLD (Hutton et al, 2009). The second phase of the plant extended the capacity with 8–10 MLD intended for industrial use, and was completed in 2010 (Bhagwan, 2012). In 2013, the plant was further upgraded in order to add a further 20 MLD to its capacity. This upgrade is currently being commissioned and will result in a total capacity of 50 MLD.

CS7.1.3 Plant ownership

The development of the eMalahleni water reclamation plant, at a cost of Rand 296 million, was well beyond the capability of the eMalahleni Municipality to fund (Bhagwan, 2012). The municipality therefore entered into a public-private partnership agreement between themselves, Anglo American Thermal Coal and BHP Billiton (Bhagwan, 2012). The plant is owned by Anglo American Thermal Coal. The plant was contracted under a design, build, operate and maintain contract, which is currently with Aveng Water. The eMalahleni Municipality, in turn, buys the water supplied by the plant to the local water distribution network.

CS7.2 Establishment of the potable reuse scheme

CS7.2.1 Feedwater source

The feed to the plant comes from four different mines, Greenside, Kleinkopje, South Witbank and Landau. These mines all lie within the catchment area from which the eMalahleni Municipality abstracts water for the town. The catchment area receives an average annual rainfall of 800 mm (Naidu, 2012). Combined, these mines have accumulated more than 100 GL of AMD, which is a major environmental risk due to uncontrolled discharge. The water received from the four mines have different qualities; therefore, a feedwater pond was constructed (two-day retention time) which receives all the feeds from the mines before it is pumped to the plant (Hutton et al, 2009).

CS7.2.2 Stakeholders

The area surrounding the plant is well-known for its large number of mines and mining activities. Apart from the mines, there are also many power stations in the area, responsible for generating approximately 70% of South Africa's electricity.

The mine closure operations of BHP Billiton Energy Coal South Africa have been responsible for closing several defunct collieries in the area surrounding eMalahleni. The company is responsible for the rehabilitation and sustainable closure of selected mines, including the Witbank South colliery (located 4 km from eMalahleni) (Mey et al, 2008). After a groundwater study by the Institute of Groundwater Studies indicated that the AMD entrapped in the Witbank South colliery would soon have started to seep into surface water sources, a mitigation plan was needed (Mey et al, 2008).

Unlike most potable reuse projects that are motivated by water shortages, the plant was built with the primary aim of reducing the amount of AMD in the mines, thus reducing the risk of contaminating the catchment area. The decision to produce potable water from the AMD was only made since the technology applied for treating the AMD also produced water suitable for potable reclamation. However, the availability of the new resource provided a response to threats to drinking-water security due to the effects of climate change on available conventional water sources (Mey et al, 2008).

The plant, therefore, has stakeholders from both the mining industry and the water supply industry. The municipality and inhabitants of eMalahleni all support this innovative use of advanced water treatment technology.

CS7.2.3 Assessment and technology demonstration before implementation

Since the initial water treatment process proved inadequate during 1994–1995, extensive pilot plant studies have been conducted in the search for treatment technologies that can provide a cost-effective solution for treating the AMD. The pilot plant studies started as early as 1994 and lasted up to 2006 and covered many technology suppliers as well as treatment processes. A summary of the pilot studies that were performed can be seen in Table CS7.1.

Several factors were identified as being keys to success for performing 10 years piloting work (Gunther & Mey, 2006):

- all the pilot plants were fully automatic
- all the pilot plants were operated 24 hours a day
- all the pilot plants had a capacity of at least 200 kL per day.

In 2004, the list of 13 heavy metal and sulfate removing technologies were reduced to a shortlist of seven technologies. The technology suppliers were then asked to provide an estimate for treating AMD. The treatment process had the following requirements and guarantees:

- 10–20 MLD treatment capacity
- full redundancy
- water recovery >95%
- engineering availability >95%
- plant utilization >95%.

Table CS7.1 Technologies evaluated during pilot studies

Type of active treatment process	Purpose of treatment	Year	Water recovery (%)
Electro-dialysis reversal	Heavy metals and sulfate removal	1994–1995	65
Reverse osmosis	Heavy metals and sulfate removal	1995–2006	97
High density sludge (lime)	Heavy metals and neutralization	1995–1999	99
High density sludge (limestone)	Heavy metals and neutralization	1995–2005	99
Biological sulfate removal (CSIROSURE)	Heavy metals and sulfate removal	2000–2004	98
Ion exchange	Heavy metals and sulfate removal	1997–1999	79
Ettringnite	Heavy metals and sulfate removal	2000	95
Electrochemical	Heavy metals and sulfate removal	1997–2000	95
Biological sulfate removal (Paques)	Heavy metals and sulfate removal	1998–2003	99
Reverse osmosis	Heavy metals and sulfate removal	2004–2005	95
Hydrothermal	Heavy metals and sulfate removal	2002–2004	95
Reverse osmosis and hydrothermal	Heavy metals and sulfate removal	2004–2005	99
Reverse osmosis	Heavy metals and sulfate removal	2004	95

Source: Gunther & Mey (2006).

The technology suppliers were asked to provide the estimate assuming a water quality derived from historical data (the 95th percentile of the worst AMD source) and capable of producing water of a very high quality (Table CS7.2).

In the end, there were two technologies that stood out, namely the biological sulfate removal process of the Council for Scientific and Industrial Research, and the high recovery precipitating RO membrane process. Despite having high water recoveries, the cost of waste disposal was still significant and an additional waste disposal cost-benefit analysis was performed to provide the most cost-effective technology supplier for this application (Gunther & Mey, 2006). The decision to go forward with the high recovery precipitating RO treatment process was mainly due to low life-cycle costs, high water recoveries (more than 99%) and manageable waste streams (Bhagwan, 2012).

In 2004/2005, a final demonstration plant was commissioned; it showed that the process was successful for treating the AMD, and led to a commercial agreement with Anglo Coal. The full-scale plant was constructed and commissioned two years later.

Table CS7.2 Water quality targets for technology suppliers

Parameter	Unit	Feedwater quality	Product water quality
pH	pH	3.12	7–8
Electrical conductivity	mS/m	357	<45
Acidity	mg/L $CaCO_3$	473	<300
Total dissolved solids	mg/L	3918	<40
Calcium	mg/L	536	<30
Magnesium	mg/L	164	<30
Sodium	mg/L	71	<100
Potassium	mg/L	7	<50
Sulfate	mg/L	2500	<200
Chlorine	mg/L	35	<100
Iron	mg/L	81	<0.1
Manganese	mg/L	23	<0.05
Aluminium	mg/L	16	<0.15

Source: Gunther & Mey (2006).

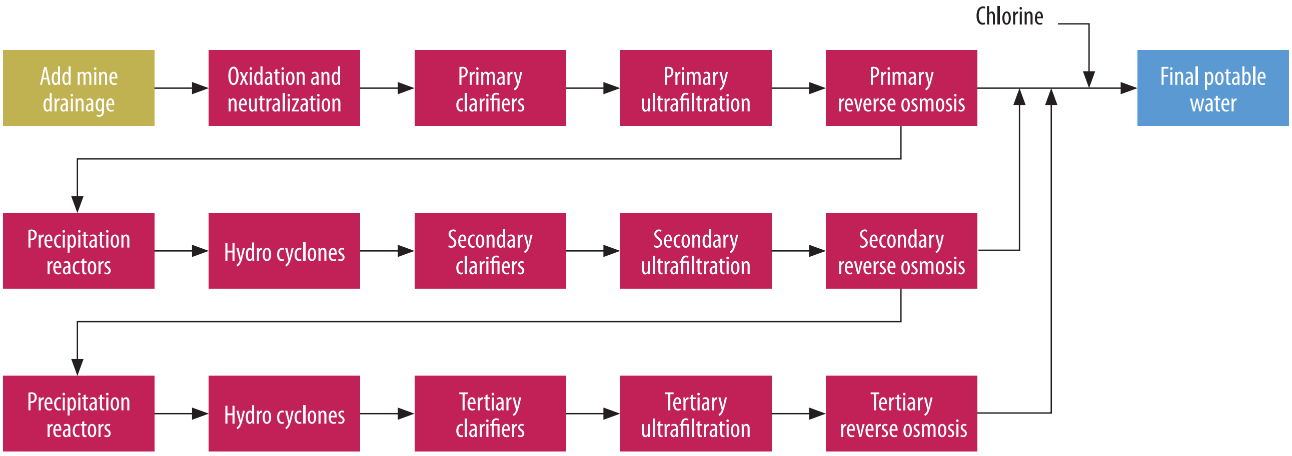
CS7.3 Control measures

The eMalahleni plant makes use of a state-of-the-art three-stage high recovery precipitating RO process capable of achieving recoveries as high as 99.7% (Hutton et al, 2009).

As shown in the treatment process flow diagram (Figure CS7.2), the first step in the treatment configuration is responsible for neutralizing the AMD, followed by clarification, UF and RO. The concentrate from the primary RO membranes is further treated by the secondary stage. The secondary and third stages both consists of precipitation reactors, hydro cyclones, clarifiers, UF and RO. Again, the concentrate from the secondary RO membranes is further treated in the third stage. The only surplus brine produced by the plant is from the tertiary RO treatment.

Permeate from each of the three RO stages are combined and chlorinated for final disinfection, followed by on-site storage in an engineered buffer. The treated water is then pumped to the potable water reservoir of the eMalahleni municipal water distribution system as well as to local mining operations. The potable water produced by the plant accounts for approximately 20% of the total demand of the eMalahleni Municipality (Lazenby, 2011).

Figure CS7.2 eMalahleni water reclamation plant flow diagram



Source: Hutton et al (2009).

CS7.3.1 Plant control and treatment philosophy

Plant control is of major importance when it comes to operating and maintaining a plant running at more than 99% water recoveries. It is for this reason that the treatment plant is situated between two large engineered buffers. The first is the raw water pond, which has a retention time of two days. The second engineered buffer is two final water reservoirs that are used in addition to the municipal reservoir which feeds the distribution network of the town.

It is therefore clear that careful control of the whole water supply system, from source to clean water storage, is of great importance to the plant operators. The plant itself makes use of a multiple-barrier process with six treatment barriers. The plant uses real-time process monitoring, on-site quality control, as well as external quality analysis from a South African National Accreditation System accredited laboratory (Naidu, 2012).

Integrity testing is one of the most important aspects of the operation and maintenance of the plant. Since the plant makes use of three stages of both UF and RO membranes, the validation of these membranes is critical. In order to protect the membranes from scaling, a monitoring programme for the calcium sulfate saturators was established. A comprehensive UF membrane performance monitoring programme is in place to minimize the risk of suspended solids breakthrough. The RO membranes are also monitored for flux, differential pressure and recovery ration, to have a clear understanding of the status of the membranes at all times (Hutton et al, 2009).

From the onset of the project, it was clear that sufficient redundancy should be built into the system. The tender for the plant stipulated that there should be at least two identical treatment trains, with a 20 MLD capacity, as well as a standby unit for each of the critical mechanical and electrical components of the plant (Gunther & Mey, 2006).

CS7.4 Water quality monitoring

CS7.4.1 Operational control monitoring

The entire treatment system is controlled using an SCADA system. The following advantages are provided by the SCADA system (Hutton et al, 2009):

- Provides pre-programmed operational modes that can be activated safely by the plant operator.
- Visual signals and confirmation are provided to the plant operator regarding the status of specific equipment (valves, pumps, etc.).
- The measurements from online instruments (sensors and probes) for plant variables are displayed to the plant operator.
- Critical process parameters are recorded and accessible for manipulation (trending, etc.).
- Abnormal conditions and faults are indicated by alarms and warnings.
- In the event of a sequence step failure, thorough feedback is provided to understand why the failure occurred.

The operational control provided by the SCADA system allows the entire plant to be run automatically. Certain sections of the plant, if they are independent from the other sections of the plant, can also be run automatically in isolation.

Plant personnel are trained in operating each of the treatment units in manual mode in case the SCADA system fails. The on-site personnel are also responsible for taking and analysing samples at the on-site laboratory in order to verify the online measurements.

A specialized maintenance information system is also available for optimizing and recording the various maintenance activities that take place on site. In addition, the system provides reports (updated weekly) important for legal compliance, work schedules and even unplanned breakdown work (Hutton et al, 2009).

CS7.4.2 Water quality monitoring

Monitoring of water quality is done daily on site to understand the process chemistry and to make process changes as required. In addition, water samples are also sent to a nearby accredited laboratory for full inductively coupled plasma analysis according to the South African national standard for potable water (SANS 241) on a monthly basis to confirm site analyses, as well as, for contractual purposes with the various clients.

Over and above the regular sampling programme, a series of eco-toxicity tests were carried out to determine if the treated water had any acute toxicity or presence of carcinogens. The results indicated that the water was not toxic to drink or had any carcinogens present.

CS7.5 Public outreach

When the initial plant was built, careful consideration was taken to employ local labour and a daily register was kept for the duration of construction. Up to 63% of the labour used on site was attributed to local labour. Any incidents or queries from the community were given serious attention and were handled with care and respect.

CS7.6 Governance

The plant was constructed, commissioned and operated with strict adherence to the Mine Health and Safety Act as well as the Occupational Health and Safety Act. In terms of the final water quality produced by the plant, the water fully complies with (SANS 241). Since the plant produces potable water to the public, it is also included in the national Blue Drop programme (Naidu, 2012).

SANS 241 provides limits for five categories of constituents which have been shown to impact health, acutely or chronically, as well as the aesthetics of the water (Tables CS7.3 and CS7.4).

Table CS7.3 SANS 241 microbial determinant limits

Parameter	Risk	Unit	Standard limits
***E. coli* or faecal coliforms**	Acute health – 1	Count per 100 ml	Not detected
Cytopathogenic viruses	Acute health – 2	Count per 10 L	Not detected
Protozoan parasites			
Cryptosporidium species	Acute health – 2	Count per 10 L	Not detected
Giardia species	Acute health – 2	Count per 10 L	Not detected
Total coliforms	Operational	Count per 100 ml	≤10
Heterotrophic plate count	Operational	Count per ml	≤1000
Somatic coliphages	Operational	Count per 10 ml	Not detected

Table CS7.4 SANS 241 physical determinant limits

Constituent	Risk	Unit	Standard limits
Free chlorine	Chronic health	mg/L	≤5
Monochloramine or equivalent for other approved disinfectants	Chronic health	mg/L	≤3
Colour	Aesthetic	mg/L Pt-Co	≤15
Conductivity	Aesthetic	mS/m	≤170
Odour or taste	Aesthetic	—	Inoffensive
Total dissolved solids	Aesthetic	mg/L	≤1200
Turbidity	Operational Aesthetic	NTU NTU	≤1 ≤5
pH	Operational	pH	5 to 9.7

SANS 241 also includes a variety of macro and micro chemicals (phosphates, nitrates, heavy metals, etc.) as well as DBPs (trihalomethanes) and other organic chemicals (TOC, phenol, microcystin, etc.).

In its strive towards continuous improvement of drinking-water management practices, the Department of Water and Sanitation Drinking-water Quality Regulation Unit is applying increasingly comprehensive criteria for water services authorities to meet during the annual assessment of water supply systems (catchment to consumer). These assessments are performed by means of the Blue Drop programme, in which a number of specific criteria are set with which the water services authorities need to comply in order to obtain Blue Drop Certification.

Blue Drop Certification criteria consist of the following sections:

- water safety plans;
- process control and maintenance programmes and documentation, including operation and maintenance manuals;
- operational and compliance water quality monitoring programmes;
- evidence of credibility of water quality results (accreditation/proficiency scheme);
- water quality results submitted to the Department of Water and Sanitation during the previous 12 months;
- compliance data (tables/graphs) of the above water quality results;
- protocols for drinking-water quality failure response management, and implementation thereof;
- publication of drinking-water quality results in newspapers, newsletters, etc.; and
- evidence of asset registers, annual process audits and maintenance.

Apart from the external regulations there are also numerous in-house regulations regarding the operation and maintenance of the various treatment units.

CS7.7 Conclusions, challenges and lessons learned

The plant has now been operational for several years and continues to produce safe, potable water to the eMalahleni community as well as reducing the risk of environmental contamination from uncontrolled discharge of AMD. The plant was the first of its kind in the world, and as such, there were many unforeseen situations, and challenges to overcome (Gunther & Mey, 2006). Fortunately, the challenges now serve as valuable lessons learned by those involved in the project, as well as those that study it.

When it comes to commissioning a plant with this design, it is important that it is not prematurely commissioned. Involving the operation and maintenance team members in the commissioning proved to be of the utmost value since they formed part of the early stage problem-solving team (Gunther & Mey, 2006). The plant hinges on the membrane treatment processes and any risk to the membranes should be carefully considered. With the exceptional recovery achieved by the plant, there are many risks factors that need to be accounted for. A thorough monitoring plan, as well as operational and emergency guidelines, is critically important (Gunther & Mey, 2006).

In conclusion, it should be noted that the plant is very sensitive and requires constant care, monitoring and operational adjustments, but if this is done correctly, by qualified personnel, the plant will be very reliable.

REFERENCES

Abbott Chalew TE, Ajmani GS, Huang H, Schwab KJ (2013). Evaluating nanoparticle breakthrough during drinking water treatment. Environmental Health Perspectives. 121(10):1161–1166. http://dx.doi.org/10.1289/ehp.1306574 (accessed 22 May 2017).

Agus E, Lim MH, Zhang L, Sedlak DL (2011). Odorous compounds in municipal wastewater effluent and potable water reuse systems. Environmental Science and Technology. 45:9347–9355.

Anderson P, Denslow N, Drewes JE, Oliveri A, Schlenk D, Snyder SA (2010). Monitoring strategies for chemicals of emerging concern (CECs) in recycled water. 220.

Angelotti RW (1995). Applying advanced treatment technology to achieve strict discharge limits. Proceedings of Education Seminar: Tertiary Treatment Technology to Meet More Stringent Water Quality Standards. Richmond (VA): Virginia Water Environment Association.

Angelotti RW, Brooks MA, Bullock AP (2014). Occurrence, fate and distribution of trace organics in the potable surface water reuse scenario of the Occoquan Watershed. Proceedings of the 18th Annual Water Reuse and Desalination Research Symposium, Las Vegas (NV). WateReuse Research Foundation, Water Research Foundation and USEPA.

Angelotti RW, Gallagher T, Brooks M, Kulik W (2005). Use of granular activated carbon as a treatment technology for implementing indirect potable reuse. Proceedings of the 20th Annual WateReuse Symposium, Denver (CO). Alexandria (VA): WateReuse Association.

Angelotti RW and Grizzard TJ (2012). Potable reuse in the Occoquan watershed. In: USEPA (United States Environmental Protection Agency) 2012 Guidelines for water reuse. EPA/625/R-04/108.

Anumol T, Sgroi M, Park M, Roccaro P, Snyder SA (2015). Predicting trace organic compound breakthrough in granular activated carbon using fluorescence and UV absorbance as surrogates. Water Research. 76:76–87.

Asami M, Aizawa T, Morioka T, Nishijima W, Tabata A, Magara Y (1999). Bromate removal during transition from new granular activated carbon (GAC) to biological activated carbon (BAC). 33:2797–2804.

Asano T, Burton FL, Leverenz H, Tsuchihashi R, Tchobanoglous G (2007). Water reuse: Issues, technologies, and applications. New York: McGraw-Hill.

Atmar RL, Opekun AR, Gilger MA, Estes MK, Crawford SE, Neill FH, Ramani S, Hill H, Ferreira J, Graham DY (2014). Determination of the human infectious dose-50% for Norwalk virus. Journal of Infectious Diseases. 209(7):1016–1022.

ATSE (2013). Drinking water through recycling. Melbourne, Victoria, Australia: Australian Academy of Technological Sciences and Engineering.

Bartram J, Corrales L, Davison A, Deere D, Drury D, Gordon B, Howard G, Rinehold A, Stevens M (2009). Water safety plan manual: Step-by-step risk management for drinking-water suppliers. Geneva: World Health Organization.

Bellona C, Drewes, JE, Oelker GL, Luna J, Filteau G, Amy G (2008). Comparing nanofiltration and reverse osmosis for drinking-water augmentation. Journal American Water Works Association. 100(9):102–116.

Betancourt WQ, Kitajima M, Wing AD, Regnery J, Drewes JE, Pepper IL, Gerba CP (2014). Assessment of virus removal by managed aquifer recharge at three full-scale operations. Journal of Environmental Science and Health. Part A Toxic/Hazardous Substances and Environmental Engineering. 49(14):1685–1692.

Betancourt WQ and Gerba CP (2016). Rethinking the significance of reovirus in water and wastewater. Food and Environmental Virology. DOI 10.1007/s12560-016-9250-8.

Bhagwan J (2012). Turning acid mine drainage water into drinking-water: The eMalahleni water recycling project. Washington (DC): United States Environmental Protection Agency.

Branch A and Le-Clech P (2015). National validation guidelines for water recycling: Membrane bioreactors. Brisbane, Australia: Australian Water Recycling Centre of Excellence. http://www.australianwaterrecycling.com.au/research-publications.html (accessed 22 May 2017).

Bruce GM, Pleus RC, Snyder SA (2010). Toxicological relevance of pharmaceuticals in drinking-water. Environmental Science & Technology. 44(14):5619–5626.

Bruvold WH and Daniels JI (1990). Standards for mineral content in drinking-water. Journal American Water Works Association. 82(2):59–65.

Bull RJ, Crook J, Whittaker M, Cotruvo JA (2011). Therapeutic dose as the point of departure in assessing the health hazards from drugs in drinking-water and recycled municipal wastewater. Regulatory Toxicology and Pharmacology. 60:1–19.

Burgess J (2015). Water reuse in South Africa. Water. 42(5):42–44.

Burlingame GA, Suffet IH, Khiari D, Bruchet AL (2004). Development of an odor wheel classification scheme for wastewater. Water Science and Technology. 49:201–9.

Buynder PV, Lugg R, Rodriguez C, Bromley M, Filmer J, Blair P, et al (2009). Characterising treated wastewater for drinking purposes following reverse osmosis treatment. Western Australia: Department of Health. http://ww2.health.wa.gov.au/Articles/F_I/Groundwater-replenishment-publications (accessed 2 June 2017).

CDC (2014). Interim guidance for managers and workers handling untreated sewage from individuals with Ebola in the United States. Atlanta (GA): Centers for Disease Control and Prevention. http://www.cdc.gov/vhf/ebola/prevention/handling-sewage.html (accessed 22 May 2017).

CDPH (2014). Regulations related to recycled water. California Department of Public Health. http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/lawbook/RWregulations_20140618.pdf (accessed 22 May 2017).

Chen CW and Gomez L (1988). Final report: Water quality evaluation of Occoquan Reservoir. Lafayette (CA): Systech Engineering, Inc.

Choi S and Jiang SC (2005). Real-time PCR quantification of human adenoviruses in urban rivers indicates genome prevalence but low infectivity. Applied and Environmental Microbiology. 71:7426–7433.

Clara M, Kreuzinger N, Strenn B, Gans O, Kroiss H (2005). The solids retention time – a suitable design parameter to evaluate the capacity of wastewater treatment plants to remove micropollutants. Water Research. 39(1):97–106.

Clayton AJ (2005). Personal communication to PL Du Pisani.

Cotruvo J (2014) Direct potable reuse: Then and now. World Water: Water Reuse and Desalination. 5:10–13.

Crook J, Bull R, Collins HF, Cotruvo JA, Jakubowski W (2013). Final report on examining the criteria for direct potable reuse: Recommendations of an NWRI independent advisory panel. Prepared by the National Water Research Institute for Trussell Technologies, Inc., under WRRF project no. 11-02. Alexandria (VA): WateReuse Research Foundation.

Dahl R (2014). Advanced thinking: Potable reuse strategies gain traction. Environmental Health Perspectives. 122(12):A332–A335.

Deere D and Khan SJ (2016). Collation and analysis of source water pathogen monitoring data. Report for NatVal 2.2 Subproject 4. http://www.australianwaterrecycling.com.au/research-publications.html (accessed 20 May 2017).

Department of Health, State of Victoria (2013). Guidelines for validating treatment processes for pathogen reduction. Department of Health, State of Victoria, Australia.

Department of Health & Water Corporation (2010). Memorandum of understanding (MoU) between the Department of Health and Water Corporation for the groundwater replenishment trial. July 2010.

Department of Statistics, Singapore (2017). Latest data (population and land area). http://www.singstat.gov.sg (accessed 23 May 2017).

Dickenson ER, Drewes JE, Sedlak DL, Wert EC, Snyder SA (2009). Applying surrogates and indicators to assess removal efficiency of trace organic chemicals during chemical oxidation of wastewaters. Environmental Science and Technology. 43(16):6242–6247.

Dieter HH (2014). Health related guide values for drinking-water since 1993 as guidance to assess presence of new analytes in drinking-water. International Journal of Hygiene and Environmental Health. 217(2–3):117–32.

Drewes JE, Anderson P, Denslow N, Olivieri A, Schlenk D, Snyder SA, Maruya KA (2013). Designing monitoring programs for chemicals of emerging concern in potable reuse – what to include and what not to include? Water Science and Technology. 67(2):433–439.

Drewes JE, Bellona C, Oedekoven M, Xu P, Kim T-U, Amy G (2005). Rejection of wastewater-derived micropollutants in high-pressure membrane applications leading to indirect potable reuse. Environmental Progress. 24(4):400–409.

Drewes JE and Horstmeyer N (2015). Recent developments in potable reuse. Vol. 45 The handbook of environmental chemistry. Switzerland: Springer International Publishing. 269–290.

Drewes JE and Khan S (2011). Water reuse for drinking-water augmentation. In: Edzwald J (ed.) Water quality and treatment, 6th edition. 16.1–16.48. Denver (CO): American Water Works Association.

Drewes JE and Khan S (2015). Contemporary design, operation and monitoring of potable reuse systems. Journal of Water Reuse and Desalination. 5(1):2–7.

Drewes JE, Sedlak D, Snyder S, Dickenson E (2008). Development of indicators and surrogates for chemical contaminant removal during wastewater treatment and reclamation. Alexandria (VA): WateReuse Research Foundation.

Duke M (2014). Demonstration of low maintenance chemical free recycling of secondary treated effluent by ceramic membranes. Australian Water Recycling Centre of Excellence. http://www.australianwaterrecycling.com.au/research-publications.html (accessed 2 June 2017).

Du Pisani PL (2006). Direct reclamation of potable water at Windhoek's Goreangab reclamation plant. Desalination. 188:79–88.

Du Pisani PL and Menge JG (2013). Direct potable reclamation in Windhoek: A critical review of the design philosophy of new Goreangab drinking-water reclamation plant. Water Science and Technology Water Supply. 13(2):214–226.

Duranceau SJ, Pfeiffer-Wilder RJ, Douglas SA, Pena-Holt N, Watson IC (2011). Post-treatment stabilization of desalinated water. Denver (CO): Water Research Foundation. 194.

DVGW (2006). UV devices for the disinfection of the water supply. German Standard W 294-1, 294-2, 294-3. German Technical and Scientific Association for Gas and Water.

DWI (2007). Desk based review of current knowledge on pharmaceuticals in drinking-water and estimation of potential levels. Final report prepared by Watts and Crane Associates for Drinking-water Inspectorate, Department for Environment, Food and Rural Affairs (Defra project code: CSA 7184/WT02046/DWI70/2/213). http://dwi.defra.gov.uk/research/completed-research/reports/dwi70-2-213.pdf (accessed 22 May 2017).

Environmental Protection Authority (2005). Strategic advice on managed aquifer recharge using treated wastewater on the Swan Coastal Plain. Environmental Protection Authority Bulletin 1199. October 2005.

Escher BI and Leusch FDL (2012). Bioanalytical tools in water quality assessment. IWA Publishing, London, UK.

Escher BI, Tang JYM, Poulsen A, Leusch FDL, Snyder SA, Jia A (2014). Development of bioanalytical techniques to assess the potential human health impacts of recycled water. Alexandria (VA): WaterReuse Research Foundation.

Ettayebi K, Crawford SE, Murakami K, Broughman JR, Karandikar U, Tenge VR, Neill FH, Blutt SE, Zeng X-L, Qu L, Kou B, Opekun AR, Burrin D, Graham DY, Ramani S, Atmar RA, Estes M (2016). Replication of human noroviruses in stem cell-derived human enteroids. Science. 353:1387–1393.

European Union (2011). Commission Recommendation of 18 October 2011 on the definition of nanomaterial. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011H0696 (accessed 20 May 2017).

FAO/WHO (2003). Hazard characterization for pathogens in food and water. Geneva: World Health Organization and Food and Agriculture Organization of the United Nations.

Fong T-T, Phanikumar MS, Xagoraraki I, Rose JB (2010). Quantitative detection of human adenoviruses in wastewater and combined sewer overflows influencing a Michigan river. Applied and Environmental Microbiology. 76:715–723.

Fono LJ, Kolodziej EP, Sedlak DL (2006). Attenuation of wastewater-derived contaminants in an effluent-dominated river. Environmental Science & Technology. 40(23):7257–7262.

Freeman G, Poghosyan M, Lee M (2008). Where will we get the water? Assessing Southern California's future water strategies. Los Angeles County Economic Development Corporation. http://www.laedc.org/sclc/documents/Water_SoCalWaterStrategies.pdf (accessed 20 May 2017).

Frenck R, Bernstein DI, Xia M, Huang P, Zhong W, Parker S, Dickey M, McNeal M, Jiang X (2012). Predicting susceptibility to norovirus GII.4 by use of a challenge model involving humans. Journal of Infectious Diseases. 206:1386–13993.

Gerrity D, Holady JC, Mawhinney DB, Quinones O, Trenholm RA, Snyder SA (2013a). The effects of solids retention time in full-scale activated sludge basins on trace organic contaminant concentrations. Water Environment Research. 85(8):715–724.

Gerrity D, Pecson B, Trussell RS, Trussell RR (2013b). Potable reuse treatment trains throughout the world. Journal of Water Supply: Research and Technology-AQUA. 62(6):321–338.

Gerrity D, Trenholm RA, Snyder SA (2011). Temporal variability of pharmaceuticals and illicit drugs in wastewater and the effects of a major sporting event. Water Research. 45(17):5399–5411.

Gibney KB, O'Toole J, Sinclair M, Leder K (2014). Disease burden of selected gastrointestinal pathogens in Australia. International Journal of Infectious Disease. 28:176–185.

Grabow WOK (1984). Guidelines for the microbiological quality of drinking-water. For the Steering Committee for Health Aspects of Water Supply: Subcommittee for Preliminary Water Quality Criteria. Microbiology Working Group. Pretoria, August 1984.

Grabow, WOK (1990). Microbiology of drinking-water treatment: Reclaimed wastewater. In: GA McFeters (ed.). Drinking-water microbiology – progress and recent developments. New York: Springer Verlag. 185–203.

Gunther P and Mey W (2006). Selection of mine water treatment technologies for the eMalahleni (Witbank) water reclamation project, Pretoria, South Africa. Water Institute of Southern Africa: Umhlanga, South Africa.

Guzman-Herrador B, Carlander A, Ethelberg S, Freiesleben de Blasio B, Kuusi M, Lund V, Löfdahl M, MacDonald E, Nichols G, Schönning C, Sudre B, Trönnberg L, Vold L, Semenza JC, Nygård K (2015). Waterborne outbreaks in the Nordic countries, 1998 to 2012. Euro Surveillance. 20(24):pii 21160. http://www.eurosurveillance.org/ViewArticle.aspx?ArticleId=21160 (15 June 2017).

Haas CN, Crockett CS, Rose JB, Gerba CP, Fazil AM (1996). Assessing the risk posed by oocysts in drinking-water. Journal of American Water Works Association. 88(9):131–136.

Health Canada (2010). Canadian guidelines for domestic reclaimed water for use in toilet and urinal flushing. Ottawa: Health Canada.

Hellmer M, Paxeus N, Magnius L, Enache L, Arnholm B, Johansson, Bergstrom T and Norder H (2014) Detection of pathogenic viruses in sewage provided early warnings of hepatitis A virus and norovirus outbreaks. Applied and Environmental Microbiology. 80(21):6771–6781.

Hijnen WAM, Beerendonk EF, Medema GJ (2006). Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: A review. Water Research. 40:3–22.

Hrudey SE and Hrudey EJ (2004). Safe drinking-water: Lessons from recent outbreaks in affluent countries. London: IWA Publishing.

Hrudey SE and Hrudey EJ (2014). Ensuring safe drinking-water: Learning from frontline experience with contamination. Denver (CO): American Water Works Association.

Huerta-Fontela M, Galceran MT, Ventura F (2008). Stimulatory drugs of abuse in surface waters and their removal in a conventional drinking-water treatment plant. Environmental Science & Technology. 42(18):6809–6816.

Hussain SM, Braydich-Stolle LK, Schrand AM, Murdock RC, Yu KO, Mattie DM, Schlager JJ, Terrones M (2009). Toxicity evaluation for safe use of nanomaterials: Recent achievements and technical challenges. Advanced Materials. 21(16):1549 –1559.

Hutton B, Kahan I, Naidu T, Gunther P (2009). Operating and maintenance experience at the eMalahleni Water Reclamation Plant, Pretoria, South Africa. IMWA.

IAWG (2008). Trial environmental values for the Leederville aquifer for the groundwater replenishment trial. Inter-Agency Working Group. February 2008.

Install SP and Zeilig N (2007). State of the science report: AwwaRF and distribution system water quality. Denver (CO): Awwa Research Foundation.

IPCC (2014). 5th assessment report. Jiménez Cisneros et al (eds). Cambridge University Press, Cambridge, United Kingdom, and New York (NY): Intergovernmental Panel on Climate Change. 229–269.

IPCS (1994). Assessing human health risks of chemicals: Derivation of guidance values for health-based exposure limits. Geneva: World Health Organization, International Programme on Chemical Safety (Environmental Health Criteria 170).

Isaäcson M, Sayed AR, Hattingh W (1987). Studies on health aspects of water reclamation during 1974 to 1983 in Windhoek, South West Africa/Namibia. Report WRC 38/1/87 to the Water Research Commission, Pretoria.

Isaäcson M, Sayed AR, Hattingh W (1988). Health aspects of the use of recycled water in Windhoek, SWA/Namibia, 1974–1983. Diarrhoeal diseases and the consumption of reclaimed water. South African Medical Journal. 21:596–599.

Jofre J and Blanch AR (2010). Feasibility of methods based on nucleic acid amplification techniques to fulfil the requirements for microbiological analysis of water quality. Journal Applied Microbiology. 109:1853–1867.

Jones MK, Grau KR, Costantini V, Kolawole AO, de Graaf M, Freiden P, Graves CL, Koopmans M, Wallet SM, Tibbetts SA, Schultz-Cherry S, Wobus CE, Vinjé J, Karst SM (2015). Human norovirus culture in B cells. Nature Protocols. 10(12):1939–47.

Keegan A, Wati S, Robinson B (2012). Chlor(am)ine disinfection of human pathogenic viruses in recycled waters. Smart Water Fund, SWF62M-2114. http://clearwater.asn.au/user-data/research-projects/swf-files/62m---2114-chlorine-disinfection-of-human-pathogenic-viruses-_final_report.pdf (accessed 20 May 2017).

King B, Fanok S, Phillips R, Lau M, Young F, van den Akker B, Monis P (2017). *Cryptosporidium* attenuation across the wastewater treatment train: Recycled water fit for purpose. Applied and Environmental Microbiology. 83:e03068.

Kommineni S, Zoeckler J, Stocking A, Liang S Flores A, Kavanaugh M (2000). Advanced oxidation processes in treatment technologies for removal of methyl tertiary butyl ether (MTBE) from drinking-water: A report written for the California MTBE Research Partnership. Melin G (ed.). National Water Research Institute. http://www.nwri-usa.org/pdfs/TTChapter3AOPs.pdf (accessed 20 May 2017).

Krasner SW (2009). The formation and control of emerging disinfection by-products of health concern. Philosophical Transactions Series A. 367:4077–4095.

Krasner SW, Westerhoff P, Chen BY, Rittmann BE, Amy G (2009). Occurrence of disinfection byproducts in United States wastewater treatment plant effluents. Environmental Science & Technology. 43(21):8320–8325.

Kroes R, Kleiner J, Renwick A (2005). The threshold of toxicological concern concept in risk assessment. Toxicological Sciences. 86(2):226–230.

Kroes R, Renwick A, Cheeseman M, Kleiner J, Mangelsdorf I, Piersmaf A, Schilterg B, Schlatter J, van Schothorste F, Vosf JG, Wurtzen G (2004). Structure-based thresholds of toxicological concern (TTC): Guidance for application to substances present at low levels in the diet. Food and Chemical Toxicology. 42: 65–83.

Law IB (2008). The future direction for potable reuse. Water. 35(8):58–63.

Law IB, Menge J, Cunliffe D (2015). Validation of the Goreangab Reclamation Plant in Windhoek, Namibia against the 2008 Australian guidelines for water recycling. Journal of Water Reuse and Desalination. 5:64–71.

Laws BV, Dickenson ERV, Johnson TA, Snyder SA, Drewes JE (2011). Attenuation of contaminants of emerging concern during surface-spreading aquifer recharge. Science of the Total Environment. 409(6):1087–1094.

Lazenby H (2011). UNFCCC endorses eMalahleni Water Reclamation Plant. Mining Weekly. 8 December 2011.

Lee D.G, Roehrdanz PR, Feraud M, Ervin J, Anumol T, Jia A, Park M, Tamez C, Morelius EW, Gardea-Torresdey JL, Izbicki J, Means JC Snyder SA, Holden PA (2015). Wastewater compounds in urban shallow groundwater wells correspond to exfiltration probabilities of nearby sewers. Water Research. 85:467–475.

Leusch FDL and Snyder SA (2015). Bioanalytical tools: Half a century of application for potable reuse. Environmental Science: Water Research and Technology. 1:606–621.

Leverenz HL, Tchobanoglous G, Asano T (2011). Direct potable reuse: A future imperative. Journal of Water Reuse and Desalination. 1:2–10.

Lodder WJ and de Roda Husman AM (2005). Presence of noroviruses and other enteric viruses in sewage and surface waters in the Netherlands. Applied and Environmental Microbiology. 71:1453–1461.

Lodder WJ, van den Berg HHJL, Rutjes SA, de Roda Husman AM (2010). Presence of enteric viruses in source waters for drinking-water production in the Netherlands. Applied and Environmental Microbiology 76:5065–5971.

Lopman B, Atmar R, Baric R, Estes M, Green K, Glass R, Hall A, Iturriza-Gomara M, Kang C, Lee B, Parashar U, Riddle M, Vinje J (2015). Global burden of norovirus and prospects for vaccine development. Atlanta (GA): Centers for Disease Control and Prevention.

MacKenzie WR, Hoxie NJ, Proctor ME, Gradus MS, Blair KA, Peterson DE, Kazmierczak JJ, Addis DG, Fox KR, Rose JB, Davis JP (1994). A massive outbreak in Milwaukee of *Cryptosporidium* infection transmitted through the public water supply. New England Journal of Medicine. 331:161–167.

Mara D, Hamilton A, Sleigh A, Karavarsamis N (2010). Discussion paper: Options for updating the 2006 WHO guidelines. In: Using human waste safely for livelihoods, food production and health. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/human_waste/en/ (accessed 20 May 2017).

Marciano-Cabral F, Jamerson M, Kaneshiro (2010). Free-living amoebae, Legionella and Mycobacterium in tap water supplied by a municipal drinking-water utility in the USA. Journal of Water and Health. 8:71–82.

Mawhinney DB, Young RB, Vanderford BJ, Borch T, Snyder SA (2011). Artificial sweetener Sucralose in U.S. drinking-water systems. Environmental Science & Technology. 45(20):8716–8722.

Meiring and Partners (Consulting Engineers) (1982). A guide for the planning, design and implementation of a water reclamation scheme. Prepared for the Water Research Commission, Pretoria.

Merel S, Anumol T, Park M, Snyder SA (2015a). Application of surrogates, indicators, and high-resolution mass spectrometry to evaluate the efficacy of UV processes for attenuation of emerging contaminants in water. Journal of Hazardous Materials. 282:75–85.

Merel S, Nikiforov AI, Snyder SA (2015b). Potential analytical interferences and seasonal variability in diethyltoluamide environmental monitoring programs. Chemosphere. 127:238–245.

Messner MJ, Berger P, Nappier SP (2014). Fractional poisson – A simple dose-response model for human norovirus. Risk Analysis. 34:1820–1829.

Metcalf & Eddy, Inc. (2003). Wastewater engineering: Treatment and reuse, 4th edition. New York: McGraw-Hill.

Mey W, Naude C, Bloy S (2008). Management of the South Witbank Colliery decant: eMalahleni water reclamation plant's untold story. Water Institute of Southern Africa: Umhlanga, South Africa.

Moreira NA and Bondelind M (2017). Safe drinking water and waterborne outbreaks. Journal Water and Health. 15(1):83–96.

Mosher JJ, Vartanian GM, Tchobanoglous (2016). Potable reuse research compilation: Synthesis of findings. Alexandria (VA): Water Environment and Research Foundation. http://www.nwri-usa.org/pdfs/Reuse-15-01-web-(2).pdf (accessed 20 May 2017).

Munro IC, Renwick AG, Danielewska-Nikiel B (2008). The threshold of toxicological concern (TTC) in risk assessment. Toxicology Letters. 180(2):151–156.

Naidu T (2012). The eMalahleni Water Reclamation Project: A South African case study. Water Institute of Southern Africa: Umhlanga, South Africa.

Nancarrow BE, Leviston Z, Tucker DI (2009). Measuring the predictors of communities' behavioural decisions for potable reuse of wastewater. Water Science and Technology. 60(12):3199 –3209.

NEA (2008). Environmental Public Health (Quality of Piped Drinking-water) Regulations 2008. National Environment Agency: Singapore. http://www.nea.gov.sg/public-health/piped-drinking-water-quality (accessed 23 May 2017).

Neale PA, Jämting ÅK, Escher BI, Herrmann J (2012). The fate of engineered nanomaterials in wastewater. Final Report WaterRA project 2025. Adelaide: Water Research.

Nellor MH, Baird RB, Smyth JR (1984). Health effects study. Final report. County Sanitation Districts of Los Angeles County.

Nelson ED, Do H, Lewis RS, Carr SA (2011). Diurnal variability of pharmaceutical, personal care product, estrogen and alkylphenol concentrations in effluent from a tertiary wastewater treatment facility. Environmental Science & Technology. 45(4):1228–1234.

NHMRC-NRMMC (2011). Australian Drinking Water Guidelines. National Health and Medical Research Council, National Resource Management Ministerial Council, Australian Government.

Nielsen E, Østergaard G, Larsen GC (2008). Toxicological risk assessment of chemicals: A practical guide. New York: Informa Healthcare.

NRC (1998). Issues in potable reuse. National Research Council. Washington (DC): National Academies Press.

NRC (2012). Water reuse: Potential for expanding the nation's water supply through reuse of municipal wastewater. National Research Council. Washington (DC): National Academies Press.

NRMMC-EPHC-NHMRC (2008). Australian Guidelines for Water Recycling: Managing health and environmental risks (Phase 2): Augmentation of drinking-water supplies. National Resource Management Ministerial Council, Environment Protection and Heritage Council, National Health and Medical Research Council, Australian Government.

NRMMC-EPHC-NHMRC (2006–2009). Australian guidelines for water recycling: Managing health and environmental risks. National Resource Management Ministerial Council, Environment Protection and Heritage Council, National Health and Medical Research Council, Australian Government.

NWRI (2013). Examining the criteria for direct potable reuse. National Water Research Institute independent advisory panel final report prepared for Trussell Technologies, Inc. under WateReuse Research Foundation project no. 11-02.

NWRI (2015). Framework for direct potable reuse, a National Water Research Institute independent advisory panel final report prepared for the WateReuse Association, co-sponsored by the American Water Works Association and the Water Environment Federation.

NWRI (2016). Final report of an NWRI independent advisory panel: Recommended DPR general guidelines and operational requirements for New Mexico. Fountain Valley (CA): National Water Research Institute. http://www.nwri-usa.org/pdfs/New-Mexico-DPR-Panel-General-Report(1).pdf (accessed 20 May 2017).

Olivieri AW, Crook J, Anderson MA, Bull RJ, Drewes JE, Haas CN, Jakubowski W, McCarty PL, Nelson KL, Rose JB, Sedlak DL, Wade TJ (2016). Expert panel final report: Evaluation of the feasibility of developing uniform water recycling criteria for direct potable reuse. Prepared August 2016 by the National Water Research Institute for the State Water Resources Control Board, Sacramento (CA).

ÖNORM (2001). Plants for disinfection of water using ultraviolet radiation – Requirements and testing: Low pressure mercury lamp plants. Austrian Standard 5873-1.

ÖNORM (2003). Plants for disinfection of water using ultraviolet radiation – Requirements and testing: Medium pressure mercury lamp plants. Austrian Standard 5873-2.

Onyango L, Leusch F, Leslie G, Wood JG (2015). Water quality and public health: Risks and prevention, health assessments and potable use case studies. Brisbane, Australia: Australian Water Recycling Centre of Excellence. http://www.australianwaterrecycling.com.au/research-publications.html (accessed 20 May 2017).

Ort C, Lawrence MG, Reungoat J, Mueller JF (2010). Sampling for PPCPs in wastewater systems: Comparison of different sampling modes and optimization strategies. Environmental Science & Technology. 44(16):6289–6296.

Pang L (2009). Microbial removal rates in subsurface media estimated from published studies of field experiments and large intact soil cores. Journal of Environmental Quality. 38:1531–1559.

Pecson B, Trussell RS, Pisarenko A, Trussell RR (2015), Achieving reliability in potable reuse: The Four Rs. Journal of American Water Works Association. 107(3):48–58.

Peet JR, Kippin SJ, Marshall JS, Marshall JM (2001). Water quality impacts from blending multiple water quality types. Denver (CO): Awwa Research Foundation.

Petterson S, Signor R, Ashbolt N, Roser D (2006.) Quantitative microbial risk assessment in the water safety plan. https://www.kwrwater.nl/wp-content/uploads/2016/09/MICRORISK-FINAL-REPORT-Quantitative-microbial-risk-assessment-in-the-Water-Safety-Plan.pdf (accessed 2 June 2017).

Pipe-Martin C, Reungoat J, Keller J (2010). Dissolved organic carbon removal by biological treatment. Water Quality Research Australia Research Report 76.

Pouillot R, Van Doren JM, Woods J, Plante D, Smith M, Goblick G, Roberts C, Locas A, Hajen W, Stobo J, White J, Holtzman J, Buenaventura E, Burkhardt III W, Catford A, Edwards R, DePaola A, Calcib KR (2015). Meta-analysis of the reduction of norovirus and male-specific coliphage concentrations in wastewater treatment plants. Applied and Environmental Microbiology. 81:4669–4681.

PUB (2002). Singapore Water Reclamation Study Expert Panel Review and Findings June 2002.

PUB (2016). Our water, our future. http://www.pub.gov.sg (accessed 23 May 2017).

PUB (2017). Singapore's fifth NEWater plant opens. http://www.pub.gov.sg (accessed 23 May 2017).

Pype M-L, Alvarez de Eulate A, Arrigan D, Busetti F, Le-Clech P, Gernjak W (2015). Development of validation protocols for reverse osmosis membranes in water recycling. Brisbane, Australia: Australian Water Recycling Centre of Excellence. http://www.australianwaterrecycling.com.au/research-publications.html (accessed 20 May 2017).

Rattier M, Reungoat J, Gernjak W, Keller J (2012). Organic micropollutant removal by biological activated carbon filtration: A review. Urban Water Security Research Alliance Technical Report No. 53. http://www.urbanwateralliance.org.au/publications/UWSRA-tr53.pdf (accessed 20 May 2017).

Reclamation Technical Subcommittee (1973). Recommendations by the Technical Subcommittee. May 1973. Windhoek Reclamation Plant Technical Subcommittee Report. Windhoek, Namibia.

Redding AM, Cannon FS, Snyder SA, Vanderford BJ (2009). A QSAR-like analysis of the adsorption of endocrine disrupting compounds, pharmaceuticals, and personal care products on modified activated carbons. Water Research. 43(15):3849–3861.

Regli S, Rose JB, Haas CN, Gerba CP (1991). Modeling the risk from *Giardia* and viruses in drinking-water. Journal AWWA. 83(11):76–84.

Rice J and Westerhoff P (2015). Spatial and temporal variation in de facto wastewater reuse in drinking-water systems across the USA. Environmental Science & Technology. 49:982–989.

Rice J, Wutich A, Westerhoff P (2013). Assessment of de facto wastewater reuse across the US: Trends between 1980 and 2008. Environmental Science & Technology 47(19):11099–11105.

Ritter, Totman C, Krishnan K, Carrier R, Vezina A Morisset V (2007). Deriving uncertainty factors for threshold chemical contaminants in drinking-water. Journal of Toxicology and Environmental Health Part B – Critical Reviews. 10(7):527–557.

Robbins Jr MH (1993). Supplementing a drinking-water supply with reclaimed Water. Proceedings AWWA Annual Conference and Exposition, San Antonio (TX).

Robbins Jr MH and Gunn GA (1979). Water reclamation for reuse in Northern Virginia. Proceedings Water Reuse Symposium. Denver (CO): AWWA.

de Roda Husman AM, Lodder, WJ, Rutjes SA, Schijven JF, Teunis PFM (2009). Long-term inactivation study of three enteroviruses in artificial surface and groundwaters, using PCR and cell culture. Applied and Environmental Microbiology. 75: 1050–1057.

Rodriguez RA, Pepper IL, Gerba CP (2009). Application of PCR-based methods to assess the infectivity of enteric viruses in environmental samples. Applied and Environmental Microbiology. 75:297–307.

Rodriguez C, Weinstein P, Cook A, Devine B, Van Buynder P (2007). A proposed approach for the assessment of chemicals in indirect potable reuse schemes. Journal of Toxicology and Environmental Health Part A 70(19):1654–1663.

Ruetten J (2004). Best practices for developing indirect potable reuse projects: Phase 1 report. Alexandria (VA): WateReuse Foundation. 43–47.

Rutjes SA, Lodder WJ, Docters van Leeuwen A, de Roda Husman AM (2009). Detection of infectious rotavirus in naturally contaminated source waters for drinking-water production. Journal Applied Microbiology. 107:97–105.

Salveson A, Steinle-Darling E, Trussell S, Trussell B, McPherson L (2015). Guidelines for engineered storage for direct potable reuse. Final report to the WateReuse Association, Alexandria (VA).

Schwab BW, Hayes EP, Fiori JM, Mastrocco FL, Roden NM Cragin D, Meyerhoff RD, D'Aco VJ, Anderson PD (2005). Human pharmaceuticals in US surface waters: A human health risk assessment. Regulatory Toxicology and Pharmacology. 42(3):296–312.

Scientiae (1967). Council for Scientific and Industrial Research monthly journal, Pretoria, 1967.

Scientiae (1969). Water reclamation in Windhoek. Scientiae, Council for Scientific and Industrial Research monthly journal, Pretoria, January 1969.

Seah H and Woo CH (2012). The multiple barrier safety approach for indirect potable use and direct nonpotable use of NEWater. 2012 Guidelines for water reuse. United States Environment Protection Agency (USEPA). EPA/625/R-04/108.

Sedmak G, Bina D, MacDonald J, Couillard L (2005). Nine-year study of the occurrence of culturable viruses in source water for two drinking-water treatment plants and the influent and effluent of a wastewater treatment plant in Milwaukee, Wisconsin (August 1994 through July 2003). Applied and Environmental Microbiology. 71:1042–1050.

Seitz SR, Leon JS, Schwab KJ, Lyon GM, Dowd M, McDaniels M, Abdulhafid G, Fernandez ML, Lindesmith LC, Baric RS, Moe CL (2011). Norovirus infectivity in humans and persistence in water. Applied and Environmental Microbiology. 77:6884–6888.

Sgroi M, Roccaro P, Oelker GL, Snyder SA (2015). *N*-Nitrosodimethylamine (NDMA) formation at an indirect potable reuse facility. Water Research. 70:174–183.

Sgroi M, Roccaro P, Oelker GL, Snyder SA (2016). *N*-Nitrosodimethylamine (NDMA) formation during ozonation of wastewater and water treatment polymers. Chemosphere. 144:1618–1623.

Singh S, Henderson RK, Baker A, Stuetz RM, Khan SJ (2012). Characterisation of reverse osmosis permeates from municipal recycled water systems using fluorescence spectroscopy: Implications for integrity monitoring. Journal of Membrane Science. 421–422:180–189.

Snyder SA (2014). Emerging chemical contaminants: Looking for better harmony. Journal American Water Works Association. 106(8):38–52.

Snyder SA, Adham S, Redding AM, Cannon FS, DeCarolis J, Oppenheimer J, Wert EC, Yoon Y (2007). Role of membranes and activated carbon in the removal of endocrine disruptors and pharmaceuticals. Desalination. 202:156–181.

Snyder SA, Leising J Westerhoff P, Yoon Y, Mash H, Vanderford BJ (2004). Biological and physical attenuation of endocrine disruptors and pharmaceuticals: implications for water reuse. Groundwater Monitoring & Remediation. 24(2):108–118.

Snyder SA, Trenholm RA, Snyder EM, Bruce GM, Pleus RC, Hemming JDC (2008). Toxicological relevance of EDCs and pharmaceuticals in drinking-water. Denver (CO): Awwa Research Foundation.

Soller JA, Eftim SE, Warren I, Nappier SP (2016). Evaluation of microbiological risks associated with direct potable reuse. Microbial Risk Analysis. http://dx.doi.org/10.1016/j.mran.2016.08.003.

Stander GJ and Van Vuuren LRJ (1969). The reclamation of potable water from wastewater. Journal Water Pollution Control Federation. 41(3):355–367.

Steinle-Darling E, Salveson A, Sutherland J, Burch J Womack J, Walker C (2015). Water quality testing at the Raw Water Production Facility in Big Spring, Texas paves the road for future direct potable reuse projects. Presented at WateReuse California in Los Angeles (CA) on 17 March 2015.

Suffet IH and Rosefeld P (2007). The anatomy of odour wheels for odours of drinking water, wastewater, compost and the urban environment. Water Science and Technology. 55(5):335–344.

Swayne MD, Boone GH, Bauer D, Lee JS (1980). Wastewater in receiving waters at water supply abstraction points. United States Environment Protection Agency (USEPA). EPA-600/2-80-044.

SWCB (1971). A policy for wastewater treatment and water quality management in the Occoquan Watershed. Richmond (VA): Virginia State Water Control Board.

SWRCB (2013). Resolution No. 2013-0003. Recycled Water Policy Amendment. California State Water Resources Control Board. Sacramento (CA): California Environmental Protection Agency.

Tan YS, Lee TJ, Tan K (2008). Clean, green and blue: Singapore's journey towards environmental and water sustainability. Singapore: Institute of Southeast Asian Studies.

Tao GH, Kekre K, Qin JJ, Ting CL, Oo MH, Viswanath B, Seah H (2006). MBR-RO for high-grade water (NEWater) production from domestic used water. Water Practice and Technology. 1(2). DOI: 10.2166/wpt.2006.041.

Taylor, JS, Dietz JD, Randall AA, Hong SK, Norris CD, Mulford LA, Arevalo JM, Imran S, Puil ML, Liu S, Mutoti I, Tang J, Xiao W, Cullen C, Heaviside R, Mehta A, Patel M, Vasquez F, Webb D (2005). Effects of blending on distribution system water quality. Denver (CO): Awwa Research Foundation and Tampa Bay Water.

Taylor, JS, Dietz JD, Randall AA, Norris CD, Alshehri A, Arévalo J, Guan X, Lintereur P, MacNevin D, Stone E, Vaidya R, Zhao B, Glatthorn S, Shekhar A (2008). Control of distribution system water quality using inhibitors. Denver (CO): Awwa Research Foundation and Tampa Bay Water.

Teunis PFM, Moe CL, Liu P, Miller S E, Lindesmith L, Barie RS, Pendu J L, Calderon R L (2008). Norwalk virus: How infectious is it? Journal of Medical Virology. 80:1468–476.

Tchobanoglous G, Leverenz H, Nellor MH, Crook J (2011). Direct potable reuse: A path forward. Washington (DC): WateReuse Research and WateReuse California.

Tchobanoglous G, Cotruvo J, Crook J, McDonald E, Olivieri A, Salveson A, Trussell RS (2015). Framework for direct potable reuse (2015). Alexandria (VA): WateReuse Research Foundation. Water Environment & Reuse Foundation report number Reuse-14-20.

Thompson T, Fawell J, Kunikane S, Jackson D, Appleyard S, Callan P, Bartram J and Kingston P (2007). Chemical safety of drinking-water: Assessing priorities for risk management. Geneva: World Health Organization.

Trussell RR, Salveson A, Snyder SA, Trussell RS, Gerrity D, Pecson BM (2013). Potable reuse: State of the science report and equivalency criteria for treatment trains. Alexandria (VA): WateReuse Research Foundation.

TWDB (2015). Final report: Direct potable reuse resource document. Austin (TX): Texas Water Development Board.

UNDESA (2014). World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352). New York: United Nations Department of Economic and Social Affairs, Population Division.

UNESCO (2017). The United Nations World Water Development Report 2017. Paris, France: United Nations Educational, Scientific and Cultural Organization.

UNSCEAR (2008). Sources and effects of ionizing radiation. Vol. 1. United Nations Scientific Committee on the Effects of Atomic Radiation. www.unscear.org/unscear/en/publications/2008_1.html (accessed 20 May 2017).

UOSA (2011). Upper Occoquan Service Authority. http://www.uosa.org (accessed 22 May 2017).

USEPA (1996). National drinking-water regulations and health advisories. EPA 822B96002. Washington (DC): United States Environmental Protection Agency.

USEPA (1999). Alternative disinfectants and oxidants guidance manual. Washington (DC): United States Environmental Protection Agency.

USEPA (2003). LT1ESTWR disinfection profiling and benchmarking technical guidance manual. Office of Water. Washington (DC): United States Environmental Protection Agency.

USEPA (2005). Membrane filtration guidance manual. EPA 815-R-06-009. Washington (DC): United States Environmental Protection Agency.

USEPA (2006a). National primary drinking-water regulations: Long term 2 enhanced surface water treatment rule: Final rule 40 CFR Parts 9, 141 and 142. Federal Register Vol. 71(3). Washington (DC): United States Environmental Protection Agency.

USEPA (2006b). Ultraviolet disinfection guidance manual for the long term 2 enhanced surface water treatment rule (LT2ESWTR). EPA 815-R-06-007. Office of Water. Washington (DC): United States Environmental Protection Agency.

USEPA (2010). LT2ESWTR toolbox guidance manual. EPA 815-R-09-016. Office of Water. Washington (DC): Environmental Protection Agency.

USEPA (2011). Introduction to the National Pretreatment Program. UEP Agency. Washington (DC): United States Environmental Protection Agency.

USEPA (2012a). Guideline for water reuse. Office of Wastewater Management, Office of Water. Washington (DC): United States Environmental Protection Agency.

USEPA (2012b). Method 1623.1: *Cryptosporidium* and *Giardia* in Water by Filtration/IMS/FA. United States Environmental Protection Agency.

USEPA (2014). Table of regulated drinking-water contaminants. Washington (DC): United States Environmental Protection Agency. https://www.epa.gov/ground-water-and-drinking-water/table-regulated-drinking-water-contaminants (accessed 20 May 2017).

USEPA (2016). America recycles day 2016. Washington (DC): United States Environmental Protection Agency. https://www.epa.gov/recycle/america-recycles-day-2016 (accessed 20 May 2017).

Van Abel N, Schoen ME, Kissel JC, Meschke JS (2016). Comparison of risk predicted by multiple norovirus dose–response models and implications for quantitative microbial risk assessment. Risk Analysis. DOI: 10.1111/risa.12616.

Vanderford BJ, Drewes JE, Eaton A, Guo Y, Haghani A, Hoppe-Jones C, Schluesener M, Snyder SA, Ternes T, Wood CJ (2014). Results of an interlaboratory comparison of analytical methods for contaminants of emerging concern in water. Analytical Chemistry. 86(1):774–782.

Vanderford BJ, Drewes JE, Hoppe-Jones C, Eaton A, Haghani A, Guo Y, Snyder SA, Ternes T, Schluesener M and Wood CJ (2012). Evaluation of Analytical Methods for EDCs and PPCPs via Interlaboratory Comparison. Denver, Colorado: WateReuse Research Foundation project no. 4167.

Virginia Tech (1994). A water quality assessment for the Occoquan Reservoir: EPA clean lakes diagnostic-feasibility study. Prepared by Occoquan Watershed Monitoring Laboratory, Department of Civil and Environmental Engineering, College of Engineering. Manassas (VA): Virginia Polytechnic Institute and State University (VPI).

Wang JL and Xu LJ (2012). Advanced oxidation processes for wastewater treatment: Formation of hydroxyl radical and application. Critical Reviews in Environmental Science and Technology. 42:251–325.

Water Corporation (2009). Water forever: Towards climate resilience. October 2009.

Water Corporation (2013). Groundwater replenishment trial final report. May 2013.

Water Research Australia (2013). Engineered nanomaterials in wastewater. www.waterra.com.au/publications/document-search/?download=543 (accessed 20 May 2017).

WaterVal (2016a). Membrane bioreactor validation protocol. http://waterval.com.au/protocols/# (accessed 20 May 2017).

WaterVal (2016b). Chlorine disinfection validation protocol. http://waterval.com.au/protocols/# (accessed 20 May 2017).

WaterVal (2016c). Reverse osmosis validation protocol. http://waterval.com.au/protocols/# (accessed 20 May 2017).

WEF and AWWA (2008). Using reclaimed water to augment potable water resources, 2nd edition. Alexandria (VA): Water Environment Federation.

WHO (1963). International Standards for Drinking-water. 2nd edition. Geneva: World Health Organization. http://apps.who.int/iris/bitstream/10665/205104/2/205104_eng.pdf?ua=1 (accessed 13 June 2017).

WHO (1975). Health effects relating to direct and indirect re-use of wastewater for human consumption. Technical Paper Series. The Hague, the Netherlands: World Health Organization.

WHO (1976). Surveillance of drinking-water quality. Geneva: World Health Organization. http://apps.who.int/iris/bitstream/10665/41802/1/WHO_MONO_63.pdf (accessed 14 July 2017).

WHO (1993). Guidelines for Drinking-water Quality, 2nd edition. Volume 1 – Recommendations. Geneva: World Health Organization http://www.who.int/water_sanitation_health/publications/gdwq2v1/en/ (accessed 2 June 2017).

WHO (2003). Emerging issues in water and infectious disease. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/emergingissues/en/ (accessed 15 June 2017).

WHO (2006). Guidelines for the safe use of wastewater, excreta and greywater. Vol. II Wastewater use in agriculture. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/gsuweg2/en/ (accessed 15 June 2017).

WHO (2012). Pharmaceuticals in drinking-water. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/pharmaceuticals-in-drinking-water/en/ (accessed 15 June 2017).

WHO (2014). Ebola virus disease. Key questions and answers concerning water, sanitation and hygiene. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/WASH_and_Ebola.pdf (accessed 20 May 2017).

WHO (2015a). Sanitation safety planning: Manual for safe use and disposal of wastewater and excreta. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/ssp-manual/en/ (accessed 15 June 2017).

WHO (2015b). A practical guide to auditing of water safety plans. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/auditing-water-safety-plans/en/ (accessed 15 June 2017).

WHO (2015c). Antimicrobial resistance: An emerging water, sanitation and hygiene issue. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/antimicrobial-resistance/en/ (accessed 20 May 2017).

WHO (2016a). Protecting surface water for health: Identifying, assessing and managing drinking-water quality risks in surface-water catchments. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/pswh/en/ (accessed 20 May 2017).

WHO (2016b). Quantitative microbial risk assessment: Application for water safety management Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/qmra/en/ (accessed 16 June 2017).

WHO (2017a). Guidelines for Drinking-water Quality, 4th edition incorporating the first addendum. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/drinking-water-quality-guidelines-4-including-1st-addendum/en/ (accessed 20 May 2017).

WHO (2017b). Water quality and health – Review of turbidity: Information for regulators and water suppliers. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/turbidity-technical-brief/en/ (accessed 20 May 2017).

WHO (2017c). Chemical mixtures in source water and drinking-water. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/publications/chemical-mixtures-in-water/en/index.html (accessed 20 June 2017).

World Water Assessment Programme (2009). The United Nations World Water Development Report 3: Water in a changing world. Paris, France: United Nations Educational, Scientific and Cultural Organization; London: Earthscan.

WRRF and NWRI (2013). Final report examining criteria for direct potable reuse. Recommendation of an independent NWRI advisory panel, WateReuse Research Foundation and National Water Research Institute. WRRF Product no. 11-02-1 and NWRI publication no. 2013-01. 16–22.

WSAA (2012). Australian sewage quality management guidelines. Water Services Association of Australia.

Xu Z, Godrej AN, Grizzard TJ (2007). The hydrologic calibration and validation of a complexly linked watershed-reservoir model for the Occoquan Watershed, Virginia. Journal of Hydrology. 345(3–4):167–183.

Yang J, Schneider OD, Jjemba PK, LeCevallier MW (2015). Microbial risk modeling for main breaks. Journal American Water Works Association. http://dx.doi.org/10.5942/jawwa.2015.107.0010.

Yu HW, Anumol T, Park M, Pepper I, Scheidler J, Snyder SA (2015). On-line sensor monitoring for chemical contaminant attenuation during UV/H_2O_2 advanced oxidation process. Water Research. 81:250–260.

Zareitalabad P, Siemens J, Hamer M, Amelung W (2013). Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) in surface waters, sediments, soils and wastewater – A review on concentrations and distribution coefficients. Chemosphere. 91:725–732.

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