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Australian Academy of Technological Sciences and Engineering (ATSE)

DRINKING WATER THROUGH RECYCLING

THE BENEFITS AND COSTS OF SUPPLYING DIRECT TO THE DISTRIBUTION SYSTEM

A REPORT OF A STUDY BY THE AUSTRALIAN ACADEMY OF TECHNOLOGICAL SCIENCES AND ENGINEERING (ATSE)

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Australian Water Recycling Centre of Excellence

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OCTOBER 2013

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ISBN 978 1 921388 25 5

Date of Publication: October 2013

Publisher:
Australian Academy of Technological Sciences and Engineering
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This work is also available as a PDF document on the ATSE website at www.atse.org.au

This project was funded by the Australian Water Recycling Centre of Excellence through the Commonwealth Government's *Water for the Future* initiative. www.australianwaterrecycling.com.au

Design and production: Coretext, www.coretext.com.au
Printing: Southern Colour
Cover: iStockphoto

Contents

Acknowledgements

The Academy is most grateful for the contributions made by the report author, the Steering Committee established to oversee the conduct of the project, and input received from the external reviewers and contributors.

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The project was overseen on behalf of the Academy by a Steering Committee:

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This project was established, managed and edited by ATSE staff, principally by Dr Andrew Hastings (Research and Policy Officer, ATSE), and Harriet Harden-Davies (Manager, Policy and Projects, ATSE). The production of this publication was overseen by Bill Mackey (Deputy CEO, ATSE).

The draft report was reviewed by Mr David Smith (Managing Director of WateReuse California), and Dr Bahman Sheikh (Research Advisory Board member, National Water Research Institute, USA).

ATSE gratefully acknowledges the input provided to this project by participants in the stakeholder survey, and by Dr David de Haas and GHD through the hypothetical scenario case study modelling of alternative water supply options.

This project was funded by the Australian Water Recycling Centre of Excellence (AWRCE) through the Commonwealth Government's *Water for the Future* initiative. The opinions expressed herein are attributed to ATSE and may not reflect the views of supporting organisations.

Executive Summary

Supplying highly treated reclaimed water directly to a drinking water distribution system is known internationally as direct potable reuse (DPR). This differs from more established approaches to potable water recycling by the absence of a so-called 'environmental buffer', a practice referred to as indirect potable reuse (IPR). IPR involves the storage of treated reclaimed water in environmental buffers – such as a river, lake, reservoir or aquifer – prior to it being recovered through drinking water treatment plants and distributed to consumers.

To ATSE's knowledge at the time of publication, there are no currently operating DPR projects in Australia and no specific proposals for their development. However, ongoing interest in sustainable water supply systems, advances in the science and engineering of water treatment, and recent international developments in DPR have prompted consideration of DPR as a potential future component of Australian water supply systems.

Any DPR scheme, as considered in this report, includes a number of general characteristics. A source of municipal wastewater is required, such as effluent from wastewater treatment plants, which is purified using advanced water treatment processes to effectively and reliably remove hazardous substances including pathogens and toxic chemicals. It would not be possible to meet all demand for drinking water through recycling, so the use of additional water sources remains essential. Finally, most DPR projects require a means of blending the recycled water with conventionally sourced water prior to delivery to consumers. Conceptually, DPR can be developed in a number of alternative configurations which differ by their arrangement of the water sources, treatment processes and blending locations.

The major difference between DPR and IPR, i.e. the use of environmental buffers, has been attributed a number of important functions. These include: additional treatment of pathogens and chemical contaminants; the provision of 'time to respond' to potential water treatment incidents; and improvement of public perceptions of potable water reuse. In order to maintain appropriate levels of safety, reliability, and public acceptance, such functions would need to be performed in any DPR system by engineered or other processes. This requires sophisticated approaches to water quality monitoring techniques, process reliability assessment, personnel training, engineered water storage design, and community engagement in particular.

It is instructive to observe that there are a number of successfully operating DPR schemes internationally. The most established of these has been operating in Namibia since 1968 without observed negative impacts to public health. More recently, DPR projects have been developed in the US and South Africa, with both countries now actively considering additional developments within the next few years. Recent Guidelines for Water Reuse developed by the US Environment Protection Agency state that *"While DPR is still an emerging practice, it should be evaluated in water management planning, particularly for alternative solutions to meet urban water supply requirements that are energy intensive and ecologically unfavourable"*. The State of California, in particular, is currently investigating the feasibility of developing uniform criteria for DPR.

Potential benefits of DPR, relative to IPR, are likely to be highly case-specific. However, potential benefits include significantly lower energy requirements, construction costs, and operational costs. DPR can also provide an opportunity to allow potable reuse in situations where a suitable environmental buffer is not available for IPR.

Potential obstacles or disadvantages for DPR, relative to IPR, are primarily related to public perception and acceptance. Importantly, ATSE considers that the scientific and engineering hurdles to implementing safe and reliable DPR are manageable. However, a number of technical issues relating to the functions of an environmental buffer in IPR are described above and would need to be addressed to the satisfaction of the general community. Key among these issues is the need to ensure reliability.

It is apparent from a review of Australian legislation and regulations that existing frameworks for the planning, approval, management, and oversight of drinking water quality and recycled water in Australia could accommodate a well-designed and operated DPR project as a water resource management option. Advanced risk assessment and risk management tools are now available which can be considered for the implementation of DPR projects, relative to more established or conventional water sources.

Findings

The science, technology and engineering associated with DPR have been rapidly advancing in recent decades. DPR is growing internationally and will be an expanding part of global drinking water supply in the decades ahead.

DPR is technically feasible and can safely supply drinking water directly into the water distribution system, but advanced water treatment plants are complex and need to be designed correctly and operated effectively with appropriate oversight. Current Australian regulatory arrangements can already accommodate soundly designed and operated DPR systems.

High levels of expertise and workforce training within the Australian water industry are critical. These must be supported by mechanisms to ensure provider compliance with requirements to use appropriately skilled operators and managers in their water treatment facilities. This will be no less important for any future DPR implementation and to maintain high levels of safety with current drinking water supply systems.

Some members of the community are concerned about the prospect of DPR. Planning, decision-making and post-implementation management processes should acknowledge and respond to these concerns. Public access to information and decision-making processes needs to be facilitated. However, the relative merits of water supply options should, as far as possible, be based on quantifiable or evidence-based factors such as public safety, cost, greenhouse gas emissions and other environmental impacts, as well as public attitudes. There is little value in distinguishing DPR from other water supply options, unless specific proposals are compared using these criteria. Any proposal to consider DPR alongside alternative water supply options should explicitly take account of full life-cycle costs, long-term sustainability (including pricing) and full costing of externalities.

Individual recycling schemes, as with other supply options, will present unique opportunities and risks that need to be systematically identified and managed. In ATSE's view, the Australian Guidelines for Water Recycling provide an appropriate framework for managing community safety and for guiding responsible decision-making.

Ultimately, water supply decision-making should be based on an objective assessment of available water supply options to identify the most economically, environmentally and socially sustainable solution. While optimum solutions will continue to be case-specific, ATSE is convinced of the technical feasibility and safety of drinking water supply through DPR when properly managed. ATSE considers there can be considerable environmental, economic, and community benefits of supplying highly treated recycled water direct to drinking water distribution systems in suitable circumstances.

ATSE therefore concludes that DPR should be considered on its merits – taking all factors into account – among the range of available water supply options for Australian towns and cities. Furthermore, ATSE is concerned that DPR has been pre-emptively excluded from consideration in some jurisdictions in Australia in the past, and these decisions should be reviewed.

Governments, community leaders, water utilities, scientists, engineers and other experts will need to take leadership roles to foster the implementation and acceptance of any DPR proposal in Australia.

Recommendations

To stimulate adoption of DPR where appropriate, ATSE recommends:

Regulation

Regulation of drinking water quality should be health-based

Government regulators should implement 'health-based targets' for water quality as the primary regulatory objective for drinking water supply.

Harmonise guidelines to improve management and regulation of DPR projects

The Australian Drinking Water Guidelines and Australian Guidelines for Water Recycling should be amended as necessary to facilitate the safe management and regulation of DPR projects, and to remove uncertainties over which guidelines prevail in some circumstances relating to potable reuse.

Oversight

Implement external auditing of water quality management

Regulators should enhance external auditing of water quality management systems to help utilities and agencies maintain and demonstrate capacity to deliver safe drinking water through DPR.

Enhance capabilities and powers of regulators

Governments must resource regulators' capabilities to fully understand the complexities and challenges of managing and monitoring DPR schemes, and to either audit schemes themselves or critically assess third-party audits.

Research and development

Improve water treatment process reliability, monitoring and validation

Providers and regulators should examine world's best practice DPR facilities, and focus research and development on the optimisation, assessment and validation of water treatment process reliability and monitoring capabilities to prevent unsafe water from being delivered to customers.

Community engagement

Establish DPR reference sites around Australia and develop community engagement programs about water reuse

Providers and regulators should collaborate to develop community engagement initiatives to raise awareness of the potential advantages of both IPR and DPR, and address perceived safety concerns about recycled water. This must include the development of reference sites to facilitate further training, research, and community engagement.

List of Abbreviations used in this Report

ADWG	Australian Drinking Water Guidelines
AGWR	Australian Guidelines for Water Recycling
AOP	Advanced oxidation process
ATSE	Australian Academy of Technological Sciences and Engineering
AWT	Advanced water treatment
AWTP	Advanced water treatment plant
CCPP	Calcium carbonate precipitation potential
CDPH	Californian Department of Public Health
DALYs	Disability adjusted life years
DBP	Disinfection by-product
DOC	Dissolved organic carbon
DPR	Direct potable reuse
GAC	Granular activated carbon
H_2O_2	Hydrogen peroxide
IPR	Indirect potable reuse
LRV	Log reduction value
MF	Microfiltration
NF	Nanofiltration
NGWRP	New Goreangab Water Reclamation Plant
PAC	Powdered activated carbon
RO	Reverse osmosis
SAT	Soil-aquifer treatment
STP	Sewage treatment plant
TOC	Total organic carbon
TSS	Total suspended solids
UF	Ultrafiltration
UOSA	Upper Occoquan Service Authority
UV	Ultraviolet light
WTP	Water treatment plant
WWTP	Wastewater treatment plant

Chapter 1 Introduction

A reliable supply of high quality water is essential for all Australian towns and cities. Secure water availability facilitates agriculture, commerce, recreational activities, improved amenity and healthy lifestyles. As such, safe, reliable water supply is fundamental to the provision of high quality urban living. Drinking water supplies in Australia have notoriously experienced 'boom and bust' cycles of floods and droughts. During the inevitable prolonged droughts, many water supply planning decisions have tended to have been made with an extreme sense of urgency, as conventional drinking water supplies for some of our major cities dwindled.

This sense of urgency in planning restricts the opportunity for detailed options analysis and severely impedes the ability of governments and water utilities to develop public awareness and appreciation for the benefits of some non-traditional means of supplementing water supplies. As a consequence, it is arguable that there are now a number of large water supply infrastructure projects that were initiated during the past decade which are now seen to be an imperfect fit for addressing long-term water management needs. This is reflected in some large water recycling and seawater desalination infrastructure which is currently not producing water or operating well below design capacities.

Much of Australia is now experiencing higher levels of water availability than was the case during the most recent extensive drought, termed the 'Millennium Drought' (approximately 2001–07). Consequently, there appears to be little immediate urgency to identify and assess potential additional water sources. However, it is essential that such assessment be conducted at this point in the climate cycle, rather than waiting for the next drought to arrive. This 'planning early' approach facilitates sober analysis of all issues associated with alternative water supplies. Furthermore, it enables necessary community debate and public awareness-raising to be initiated in the absence of a perceived water supply emergency and with adequate time to proceed.

New water resources could come from a variety of sources including expanded capture and use of surface runoff, i.e. rivers and lakes, increased groundwater extraction, rainwater harvesting, urban stormwater harvesting, seawater desalination and wastewater reclamation including non-potable and potable reuse. In fact, all of these sources can be expected to play important roles in future Australian water supplies.
Australia's geography, climate and culture share many common features with some parts of the US. However, due to greater population pressures, the US has tended to lead the way with the development of alternative water sources such as non-potable water reuse, indirect potable water recycling (IPR) and seawater desalination. The trend in the past has been that Australia has followed the US with the development of initial projects of each of these types one or more decades later, but often on a very large scale.

Despite the success of IPR in the US, there is currently considerable interest internationally in 'direct potable reuse' (DPR) as an alternative (Leverenz *et al.*, 2011; Arnold *et al.*, 2012). That is, municipal wastewater is highly treated to a quality suitable for direct reuse as a drinking water supply, without the inclusion of an 'environmental buffer' which is a defining characteristic of IPR. Such 'environmental buffers' have included rivers, lakes and aquifers. In addition to the long-term successful DPR scheme in Windhoek, Namibia, there have also been rapid recent developments in DPR in a number of locations in South Africa.

The environmental buffers of IPR schemes often have identifiable advantages, including storage of surplus supply, additional 'natural' treatment, the provision of 'time to react' in the case of water quality incidents, and favourable public perception. However, the rapidly growing interest in DPR reveals perceived disadvantages of the incorporation of an environmental buffer in some systems. These disadvantages have primarily been related to capital and operational costs, energy consumption and associated greenhouse gas footprint. In addition, there are a number of other possible advantages of DPR, which are yet to be explored in detail. These include improved water quality and system reliability as a consequence of reduced vulnerability to environmental factors such as extreme weather events and other catchment-related risks.

During the past decade, potable water recycling has been subject to considerable scrutiny and public discussion in Australia. Until now, this attention has been limited almost exclusively to IPR. The alternative option of DPR has commonly been dismissed as presenting too many challenges. The perceived challenges have included the ability to reliably provide sufficiently and demonstrably safe water quality, as well as overcoming negative community perceptions and anticipated opposition.

Despite these challenges, the active interest in IPR has led to rapid developments in our understanding of the capabilities of engineered treatment processes to produce exceptionally high quality drinking water. Advanced treatment processes, such as ultrafiltration, reverse osmosis and advanced oxidation were rarely used in water supply a decade ago. There are now a number of advanced water treatment plants, including recycling plants and seawater desalination plants, making use of these technologies in most of our capital cities. With this has come improved technical capacity, techniques for risk assessment, risk management and the growing confidence of Australian health regulators.

Now is the appropriate time for Australia to begin to consider the issues associated with DPR as a potential future water resource for our cities. We can anticipate some advantages and disadvantages that are consistent with those that have been identified in the US and South Africa, and others which may be uniquely Australian. Important concerns and questions of economics, public health, environmental sustainability, risk management, and community attitudes and perceptions must be addressed.

The aim of this report is to define in objective scientific, economic and social terms, the potential place of recycling directly to the drinking water distribution system, in the spectrum of available water supply options in Australia. It seeks to place water recycling for DPR in context among other water source options, including IPR, and identify barriers specific to DPR in Australia. By identifying these barriers and the ways in which they may be overcome, this report is intended to serve as a roadmap that could facilitate the deployment of recycled water for DPR in the event that it becomes a necessary water supply option in various regions around Australia.

Terminology

The terminology associated with the treatment and reuse of municipal wastewater has varied both nationally and internationally. In particular, the terms water reclamation, water reuse and water recycling have been used synonymously by some agencies. For example, the recent US EPA Guidelines for Water Reuse state that "water reuse" and "water recycling" have the same meaning, as do the terms "reclaimed water" and "recycled water". Such interchangeable use of terminology is widespread, and intended meanings are usually relatively easily understood in context. Nonetheless, the following distinctions are used in most chapters of the current report. Exceptions occur in Chapter 6, where direct quotes are provided from survey respondents.

Water reclamation: The process of 'reclaiming' wastewater, which would otherwise have been discharged to the environment, for beneficial reuse. The water reclamation process most commonly refers to the necessary additional treatment, which is required to achieve a suitable water quality standard for reuse.

Water reuse: Any of many possible secondary uses of reclaimed water. This may include potable or non-potable applications. The secondary use may or may not be the same as the primary use of the water. That is, reclaimed municipal sewage (primarily used as potable water) may again be used as a potable water supply or in a non-potable application such as crop irrigation.

Water recycling: The reuse of reclaimed water for the same or equivalent application as the primary use. A key characteristic of a recycling process is the existence of an identifiable 'cycle', as opposed to a linear chain of processes. This is not to imply that a physical cycle is required (e.g. water is recycled back to the same reservoir or aquifer from which it was sourced), but a cycle of equivalent uses (e.g. reclaimed water from an upstream city may be treated and reused as a drinking water supply in a downstream city).

Other important terms used to describe various approaches to, and aspects of, water recycling are defined in this document as follows:

Municipal water reuse: The term 'municipal' is applied to indicate that the source of reclaimed water is a municipal wastewater treatment plant (WWTP), also known as a sewage treatment plant (STP). This includes domestic wastewater (from households) and may also include commercial and industrial wastewaters. The reuse application may or may not be directly associated with municipal activities.

Non-potable water reuse: Reclaimed water is used for non-drinking applications such as irrigation, toilet flushing or industrial processes.

Potable water reuse: Reclaimed water is reused as a component of a drinking water supply. Also referred to as 'water recycling' and 'potable water recycling'.

Planned potable reuse: This term is used to describe potable reuse schemes that are publicly acknowledged as an intentional project to recycle water for potable reuse. As such, it encompasses all direct potable reuse schemes and a number of indirect potable reuse schemes, but not the much more common, de-facto water reuse. This distinction is important since it commonly implies a more formal and coordinated approach to water quality risk management than is observed with most de-facto water reuse.
Indirect potable reuse: Reclaimed water is intentionally reused to augment an environmental drinking water supply such as a river, lake or aquifer.

Direct potable reuse: Reclaimed water is reused (with or without retention in an engineered storage buffer) as a drinking water supply, without return to an environmental system such as a river, lake or aquifer. After suitable treatment, the water may be transferred directly to a municipal water treatment plant or to a drinking water distribution system. This water may or may not be blended with other water sources.

De-facto water reuse: Also commonly referred to as 'unplanned water reuse', this refers to a situation where reuse of reclaimed water is in fact practised, but not officially recognised. Common examples occur where a wastewater treatment plant from one city discharges effluent to a river which is subsequently used as a drinking water supply for another city downstream.

Conventional water sources: Refers to environmental sources of water intended for potable use. Conventional sources include surface waters, i.e. rivers and lakes, and ground waters, i.e. aquifers. Conventional sources may be subject to a range of contamination sources including effluents from STPs (in the case of de-facto water reuse). However, planned reuse of effluents from STPs (in the case of IPR or DPR) is not considered to be a conventional source.

Conventional water treatment: Describes water treatment processes that are currently in common use for the municipal treatment of water from conventional water sources for potable use. Examples include (but are not limited to) coagulation, flocculation, media filtration, and various forms of chlorine disinfection.

Conventional wastewater treatment: Describes wastewater treatment processes that are currently in common use for the treatment of municipal wastewater prior to discharge to the environment. Examples include (but are not limited to) settling, activated sludge treatment, biofiltration (tricking filters), biological nutrient removal, media filtration and chlorine disinfection.

Advanced water treatment: Describes additional treatment processes that may be applied to conventionally treated wastewater in order to improve the quality to a degree suitable for various reuse applications, including potable reuse. Examples include (but are not limited to) membrane treatment processes (for example, microfiltration, ultrafiltration, nanofiltration, reverse osmosis), advanced oxidation processes and additional disinfection processes such as ozonation or the use of ultraviolet radiation.

Chapter 2 What is DPR and how does it work in practice?

What is direct potable reuse?

The description of DPR provided in the introduction to this report indicates that reclaimed water is reused as a drinking water supply, "without return to an environmental system such as a river, lake or aquifer". Highly treated water, sourced from reclaimed municipal wastewater, may be transferred directly to a municipal drinking water treatment plant or a drinking water distribution system. This water may or may not be blended with other water sources.

The use of the term 'direct' is intended to distinguish this approach to potable water reuse from the more commonly applied and recognised alternative, IPR. The characteristic feature of all IPR schemes is that the reclaimed water is first returned to some form of environmental system, commonly referred to as an 'environmental buffer', such as a river, lake or aquifer. From that point, the water may be mixed with other conventional sources of water prior to being extracted for further treatment and use as municipal drinking water.

The absence of an environmental buffer in a DPR project does not necessarily imply that there is no capacity for storage to buffer any variability in water supply and demand. However, it would normally imply that such a storage buffer, should it be used, would be 'engineered' rather than 'environmental'. Furthermore, engineered storage buffers of DPR systems would not normally be assumed to provide any additional treatment benefit, as is often assumed for environmental buffers.

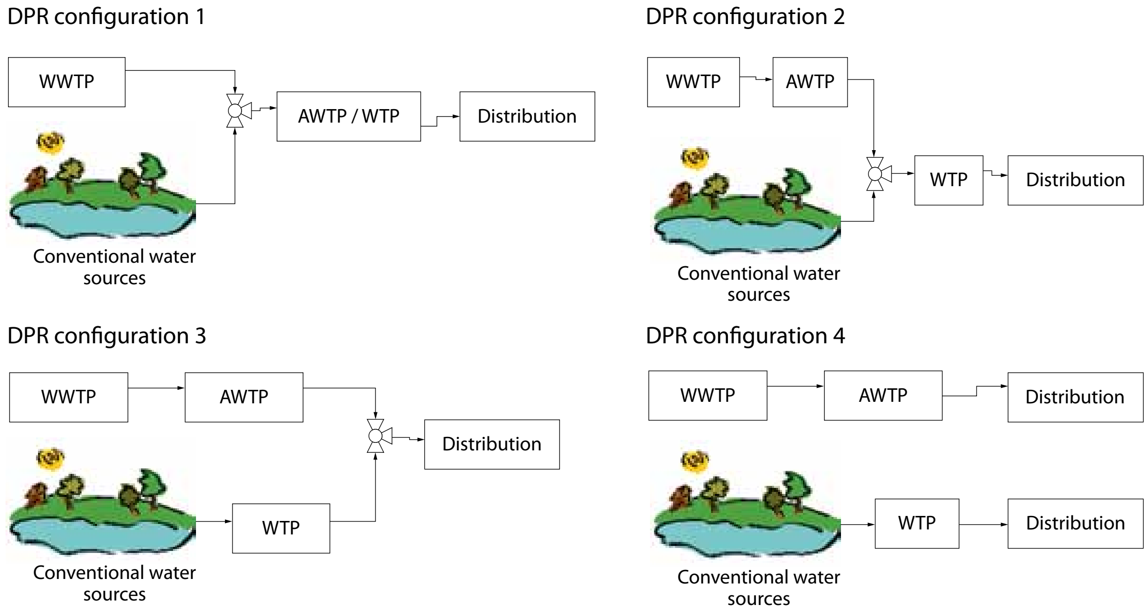
The US EPA Guidelines for Water Reuse describe DPR as follows (US EPA 2012):

> *DPR refers to the introduction of purified water, derived from municipal wastewater after extensive treatment and monitoring to assure that strict water quality requirements are met at all times, directly into a municipal water supply system. The resultant purified water could be blended with source water for further water treatment or could be used in direct pipe-to-pipe blending, providing a significant advantage of utilizing existing water distribution infrastructure.*

All direct potable water reuse projects will require a number of key components. These include a wastewater source, such as a municipal WWTP and advanced water treatment processes, which may or may not be located at a dedicated advanced water treatment plant (AWTP).

Since not all drinking water supplied to a community is returned to the wastewater collection system, additional contributions of water from conventional sources will always be required to meet demand. Conventional sources may include surface water and groundwater sources, which would also require treatment by some conventional water treatment processes. This potable water treatment may be undertaken at the same site as the advanced treatment process or at a dedicated drinking water treatment plant (WTP). Four conceptual configurations of these DPR scheme components are described in Figure 1.

Figure 1 Direct potable reuse: four configurations of water sources, treatment processes and blending.



DPR Configuration 1 involves blending of reclaimed water and conventional sources of water prior to advanced water treatment processes and any additional water treatment processes. In this case, there may be no clear distinction between processes that could be considered the 'advanced water treatment processes' and any additional 'conventional' drinking water treatment processes. Indeed, all of these processes may be located on a single site as a single plant. The New Goreangab Water Reclamation Plant in Windhoek, Namibia (see Chapter 4) is an example of this configuration.

DPR Configuration 2 involves blending of advanced-treated reclaimed water with conventionally sourced water prior to additional drinking water treatment processes. Although these additional water treatment processes will add another barrier to contaminants in reclaimed water, in most cases their primary purpose will be for treatment of the conventionally sourced component of the water. The additional water treatment process may be located separately at a dedicated drinking water treatment plant, e.g. Big Spring, Texas, or may be co-located with the advanced water treatment plant, e.g. Cloudcroft, New Mexico. Both of these examples are described in Chapter 4.

DPR Configuration 3 involves distinct treatment processes for reclaimed water and conventionally sourced water prior to blending of the two sources. In this case, the AWTP and the WTP will most commonly be located separately and blending will take place in a potable water trunk main within the distribution system. Some minor adjustments such as adjustment of disinfectant residual concentrations may still take place subsequent to blending. An example of DPR Configuration 3 is the project operating in Beaufort West Municipality, South Africa (see Chapter 4).

DPR Configuration 4 does not involve any blending of the advanced treated reclaimed water. In this case, some specific sections of a distribution system, or overall water supply system, will be supplied with unblended advanced treated reclaimed water, while other areas are supplied with conventionally sourced and treated water. Although the conventionally sourced water may, at first, appear to be unrelated to the DPR scheme, it is in fact an important component since it is required to make up the overall water balance. With the exception of some extreme circumstances (such as the International Space Station (Tchobanoglous *et al.*, 2011)), it is not feasible for a DPR scheme to operate in isolation, since some water will inevitably be lost from the system and must be continuously replaced.

Objectives of advanced water treatment process

Advanced water treatment plants are typically used to treated water for planned potable water recycling projects. AWTPs used in current potable recycling projects are variable in their design, incorporating a range of individual treatment processes, each of which also varies somewhat from one plant to another. Nonetheless, AWTPs are predominantly designed to achieve four common water treatment objectives.

The **first objective** is to reduce the concentration of the non-settleable suspended solids that carry over from conventional wastewater treatment processes. Suspended solids include colloidal material, fine particles and microorganisms such as protozoan cysts and oocysts, bacteria and viruses. Removing suspended solids improves the performance and efficiency of subsequent treatment processes used to remove dissolved chemicals and remove or provide disinfection of pathogenic microorganisms.

The **second objective** is to reduce the concentration of dissolved substances, including inorganic salts, organic molecules and residual nutrients.

The **third objective** is to provide adequate disinfection. This includes meeting specified treatment targets for pathogenic microorganisms as well as generating a residual disinfectant to maintain water quality in the final water delivery pipeline.

The **final objective** is to stabilise the water by restoring alkalinity, hardness and pH as required, to reduce aggressive or corrosive potential of highly purified water towards the materials (e.g. concrete, steel or copper) used to construct the delivery system.

A summary of the technologies most commonly used in AWTPs to achieve the objectives is provided below.

Removal of suspended solids

The first treatment objective is to reduce the concentration of total suspended solids (TSS) in effluents from conventional wastewater treatment plants. Some of the finer TSS manifest as turbidity, giving the water a ‘cloudy’ appearance. The rationale for reducing TSS and turbidity levels is to control fouling problems on downstream processes caused by colloidal and suspended particles, most notably bacteria, and to prepare the water for the final disinfection step. Treatment objectives are usually to reduce the concentration of TSS to less than 1 mg/L and turbidity to less than 1 turbidity unit.

Clarification

Prior to the early 1990s, conventional water treatment processes similar to those used in drinking water treatment plants were used to reduce the concentration of TSS. The treatment steps consisted of flash mixing and flocculation followed by clarification and granular media filtration through sand and/or anthracite (media filtration). The use of an additional clarifier provided sufficient buffering capacity and treatment residence time to deal with the temporal variations in feedwater TSS levels. This technology combination was embodied in the Californian Title 22 requirements (State of California, 2000). The choice of coagulant for the flocculation process was determined by the concentration of nutrients and heavy metals in the original wastewater. Ferric chloride applied at a pH of between 6 and 7 was used at the Windhoek plant in Namibia in 1968 (see Chapter 4) because of effective source control and biological wastewater treatment that limited the concentration of heavy metals and ammonia. In contrast, slaked lime applied to a pH of 11.4 was used in the US at Water Factory 21 in 1976, Upper Occoquan Sewage Authority (UOSA) in 1978 and West Basin in 1996 to bind residual heavy metals, and convert ammonium ions (NH_4^+) into the more volatile ammonia (NH_3) form. The metals were subsequently removed as sludge from the clarifiers, while the ammonia was removed by air stripping. A conventional treatment process using slaked lime was used in the 2004 expansion of the UOSA facility.

Sand and media filtration

A variety of particle filtration processes are used in potable water treatment and water recycling plants. These generally consist of porous beds of granular media. These *granular bed*, or *media filters* are comprised of specified depths of one or more types or sizes of granular media; rapid sand, dual-media and slow sand filters are some examples. *Depth filtration* occurs when particles deposit within the pore spaces of a filter due to transport to and attachment on the surface of the granular media or previously deposited particles. The removed particles are generally much smaller in size than the characteristic dimensions of the pore spaces through which they are transported. *Straining* or *sieving filtration* occurs when particles are prevented from passing through the pore space because of size exclusion. The selection and performance of particle filtration processes are greatly affected by raw water quality and the configuration of processes prior to filtration. However, particle filtration processes are very important in many potable water supply systems due to their ability to remove pathogenic microorganisms. They may also have important secondary roles in the overall treatment train including biological degradation of organic chemicals by the activities of biofilms present on the particulate surfaces.

Microfiltration and ultrafiltration

By the late 1990s, filtration with microporous membranes had become the preferred technology to control TSS in AWTPs. Compared to clarification and sand or media filtration, membranes require less space, use less energy and do not generate a solid sludge, which collectively reduce the cost of reclamation significantly.

Microporous membranes such as ultrafiltration (UF) and microfiltration (MF) membranes are employed for pressure driven filtration processes. The UF and MF membranes are thin, porous polymer films with nominal mean pore sizes ranging from 0.001 microns for the tightest ultrafiltration membranes through to 0.4 microns for the loosest MF membranes. Wastewater containing suspended material contacts the surface of the membrane under pressure. Initially any material larger than the pores in the membrane will be removed on a size exclusion basis (i.e. by sieving). However, operational experience, particularly with virus particles, has demonstrated that many particles smaller than the nominal pore size of the membrane are also removed as material accumulates on the surface of the membrane. Similarly, naturally occurring organic matter such as humic or fulvic acids can be removed by MF or UF membranes by first flocculating the acids using a coagulant. In addition to providing an effective barrier for many pathogenic substances, among the most important benefits of MF and UF membranes in AWTP applications is the reduction in fouling of subsequent process equipment.

UF and MF membranes used in municipal applications are generally manufactured as hollow fibres using organic polymers derived from petrochemicals. The fibres range from 1 to 2 m in length and 0.5 to 2 mm in diameter. Hollow fibre membranes are bundled together into modules. Commercial modules contain 4000 to 20,000 individual hollow fibre membranes. The module may be housed in a pressure vessel (as shown in Figure 2) or immersed in an open tank. Flat sheet microporous membranes immersed in an open tank are typically used in membrane bioreactor configurations.

For membrane elements housed in a module, the feed stream can contact either the outer surface of the fibre (shell side) or the lumen (inside) of the fibre. The microporous system can be operated in either direct or cross-flow filtration mode. During direct filtration mode , the feed water flow is perpendicular to the membrane surface and suspended solids are retained by the membrane. The accumulation of solids at the surface continuously increases the resistance to flow across the membrane. The filtration process stops after either a pre-set time, or a pre-set increase in the trans-membrane pressure, and the

Figure 2 Hollow fibre microfiltration membranes arranged in modules and housed in pressure vessels.

accumulated solids are removed from the surface by a backwash. In the cross-flow process, the feed stream is pumped across the membrane surface which establishes a velocity gradient with a minimum at the membrane surface. A variety of mechanisms including inertial lift and shear enhanced diffusion facilitate the transport of retained material away from the membrane and out of the module.

Membrane elements immersed in a tank are operated in direct filtration mode. The lumens of the hollow fibres are directly connected, via a manifold, to the suction side of a pump. When the pump operates, a vacuum on the lumen draws filtered water through the walls of fibre. Some forms of the immersed membrane design incorporate an aeration system which can be operated to continuously scour the outside of the microporous fibre to facilitate transport of retained material back into the bulk solution.

The removal efficiency of MF and UF membranes is contingent upon the mechanical integrity of the membranes, modules and filtration system. Loss of mechanical integrity results in particles and colloids passing through the filters. Loss of integrity may be attributed to physical damage by foreign bodies, chemical damage, faulty installation of components and repetitive stress induced failure at critical points (Childress *et al.*, 2005). Consequently, MF and UF systems used in drinking water and AWTPs must incorporate at least one monitoring technique that can detect broken fibres, faulty seals or leaky o-rings in real time during operation. Monitoring techniques that directly assess the integrity of the membrane system include pressure decay tests and diffusive airflow tests, while indirect tests that monitor the quality of the output include particle counting, turbidity monitoring or microbial challenge tests.

Removal of dissolved chemicals

Health departments recognise that the dissolved organic fraction of wastewater effluents may contain compounds that could impact public health. Anthropogenic or naturally occurring compounds may pass unaltered from the source water through to the inlet of the AWTP, or form as by-products or metabolites via chemical or biological pathways as wastewater passes through the treatment plant. Potential health effects include carcinogenic, toxicological, embryonic and reproductive development impacts caused by interference with the endocrine system.

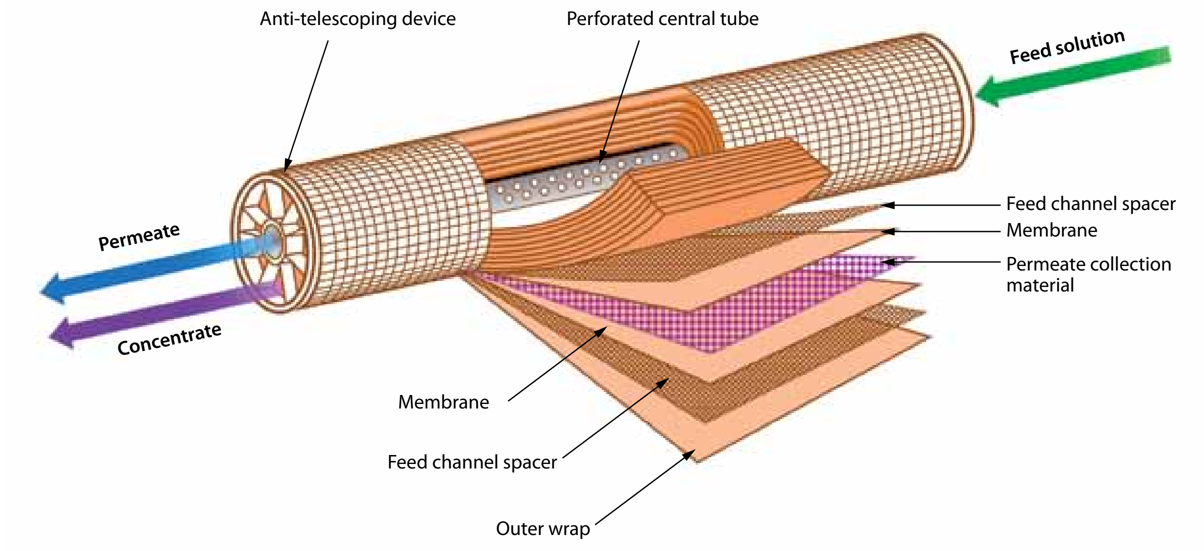
However, identification of all the compounds present in wastewater is not possible. In addition, with the exception of a few compounds, such as those listed in the *Australian Drinking Water Guidelines*, data correlating exposure via drinking water to single compounds and their expected health effects is limited. Even less data is available for mixtures of compounds. Presented with this uncertainty, the general approach to regulating potable reuse projects has usually included the requirement for a dedicated process to drastically reduce the overall concentration of dissolved organic compounds. Performance of this process may be assessed by reduction in the total organic carbon (TOC) content. The technologies used to reduce the TOC content in potable reuse projects include semi-permeable membranes such as reverse osmosis (RO) and nanofiltration (NF), activated carbon, activated carbon with ozonation, and advanced oxidation processes (AOPs) such as UV light in the presence of hydroxyl radicals.

The concentration of inorganic salts in municipal wastewater collection systems receiving discharge from domestic and industrial users is typically 200 to 400 mg/L higher than the original potable water supplies. The early Californian groundwater recharge schemes incorporated RO to reduce the concentration of dissolved salts to meet the groundwater basin objective for dissolved solids, which was equivalent to the US EPA drinking water standard of 500 mg/L. This was achieved by partially treating the water with RO.

Reverse osmosis

RO is a broad-spectrum treatment process capable of continuously removing both pathogens and dissolved chemical substances. The process is driven by a pressure gradient that forces water molecules across a semi-permeable membrane. These membranes are produced in units known as 'elements' by several manufacturers to fit commercially available RO pressure vessels.

Figure 3 Assembly of multiple reverse osmosis (RO) membrane elements into a pressure vessel.



RO membranes are configured as flat sheets. The sheets are folded over a porous spacer and sealed on three sides to create an envelope. The open side is sealed onto a perforated tube that will carry permeate that passes across the membrane and travels through the porous spacer. The active surface which is located on the outside of the envelope is wrapped in a mesh spacer. The mesh encased membrane is wound around the central permeate tube to create a spiral wound element with channels defined by the mesh spacer. Individual elements are coupled together along the permeate tube and loaded into a pressure vessel as illustrated in Figure 3.

A bank of pressure vessels (Figure 4) is connected to a high pressure feed manifold. Water under pressure is forced through the channels in each element defined by the mesh spacer. A portion of the feed water travels across the membrane and collects in the permeate tube while the balance of the water is discharged as concentrate out the end of the vessel. The ratio of permeate produced to the feed water is referred to as the process recovery. The feed pressure required is determined by the pressure loss through the channels plus the sum of the pressure loss across the membrane and the osmotic pressure of the salts retained on the membrane surface. The integrity of the membranes can be measured off-line by monitoring the ability of the permeate side to hold a vacuum.

Membrane rejection of chemical contaminants is ultimately determined by complex interactions of electrostatic and other physical forces acting between a specific solute (chemical contaminant), the solution (water and other solutes present), and the membrane itself. The nature of these forces is dependent on numerous physical properties of the solute, solution and membrane.

Bellona *et al.* (2004) have proposed a guide for estimating the removal efficiency for organic contaminants by RO based on molecular properties of the organic contaminants. This system was derived from a comprehensive review of published studies reporting variable rejection behaviour of a wide range of organic solutes by various commercially available membranes.

The most fundamental of the rejection mechanisms is size exclusion. This is a sieving process for which molecular size or geometry prevents large molecules from passing through the dense molecular structure presented by the active surface of the membrane. Size exclusion is believed to be the dominant retention mechanism for relatively large organic molecules such as surfactants, hormones, most pharmaceuticals,

Figure 4 Arrangement of pressure vessels into a single system.

proteins and other molecules with a molecular mass greater than 200 atomic mass units (or g/mol) by RO membranes (Drewes *et al.*, 2006).

Modern RO membranes, known as 'thin film composite' membranes, have been designed with chemical functional groups attached to the membrane surface to facilitate electrostatic repulsion of susceptible chemicals in the feed water. Such functional groups include sulfonic acid and carboxylic acid groups, which are negatively charged under normal pH conditions (typically between pH 6 to 8). Solutes which are also negatively charged, including many pharmaceuticals and endocrine disrupting chemicals, can be efficiently removed by such membranes (Bellona & Drewes, 2007).

Experiments with looser membranes (e.g. nanofiltration) have revealed that, under some conditions, certain chemicals are prevented from permeating the membrane due largely to adsorption onto the membrane surface (Schäfer *et al.*, 2003; Yoon *et al.*, 2006). This adsorption is believed to be due to hydrophobic interactions between relatively non-polar solutes and membranes.

The final concentration of organic molecules in the RO permeate is dependent upon the configuration of the membrane, the type of membrane and the membrane surface charge. The system operating conditions including pressure, flux and pH can also impact rejection performance of some contaminants.

Adsorptive treatment processes

For some potable reuse schemes, it may not be necessary to specifically target total dissolved solids (TDS) for removal. This may be the case where TDS content of the source water is relatively low or where there are opportunities for significant blending. Such schemes tend to employ adsorptive treatment processes to remove organic molecules. Examples include the potable reuse projects operated by the Upper Occoquan Sewage Authority (Virginia) and Gwinnett County (Georgia) in the US.

Among the most well-established processes for advanced trace organic chemical removal is adsorption to activated carbon. This is a form of carbon usually derived from charcoal. The term 'activated' refers to the way the carbon has been prepared to enhance its ability to physically 'adsorb' chemicals to its surface. An important property of activated carbon is its extremely high surface area. One gram (about a teaspoon full) of activated carbon can have a surface area of 400 to 2000m^2. By comparison, a tennis court is about 260 m^2. A microscopic view of activated carbon reveals a complex web structure intermingled with trapped smaller particles. There are many interstices, which provide excellent conditions for adsorption of suitable chemicals.

The most common forms of activated carbon for water treatment are known as granular activated carbon (GAC) and powdered activated carbon (PAC). These terms refer to the physical form, or particle size, in which the activated carbon is applied. Smaller particle sizes in PAC tend to have higher surface areas while large particle sizes in GAC tend to be more easily separated from the water subsequent to treatment. PAC is often used by direct addition to water with mixing and then separated by gravity and/or filtration. Alternatively, GAC is more commonly used as filtration media with the water being percolated through it.

The effectiveness of PAC and GAC to adsorb a particular chemical can generally be predicted based on how 'hydrophilic' or 'hydrophobic' the chemical is. These terms refer to the tendency of a chemical to partition preferentially into aqueous phases (hydrophilic) or non-aqueous phases (hydrophobic). PAC and GAC are effective for the removal of a diverse range of hydrophobic organic compounds as well as well as some relatively hydrophobic inorganic compounds such as N, sulfides and heavy metals. More hydrophilic compounds, such as small carboxylic acids and alcohols, are relatively poorly removed by activated carbon adsorption.

Figure 5 UV/H_2O_2 advanced oxidation system.

PAC has been shown to be highly effective for the removal of a wide range of pharmaceuticals, endocrine disruptors and pesticides from relatively clean water sources (Adams *et al.*, 2002; Westerhoff *et al.*, 2005). Similarly, a study reported by Ternes *et al.* (2002) revealed GAC filtration to be an effective method for removing a variety of pharmaceuticals during drinking water treatment in Europe. These studies are consistent with the conventional understanding and application of activated carbon treatment processes. Used as a component of a carefully selected suite of treatment processes, activated carbon has an important role to play in water purification.

Advanced oxidation processes

Oxidative processes may be used to degrade any organic constituents of feed water that proves to be both biologically recalcitrant and poorly retained by membranes or activated carbon. Strong chemical oxidants such as ozone, potassium permanganate and chlorine have been shown to be effective for the degradation of chemical contaminants in water.

Oxidative degradation can occur either by direct reaction with the applied oxidant, or via the production of highly reactive secondary species, most commonly hydroxyl radicals ($\cdot OH$). The hydroxyl radical is one of the most powerful oxidants known. With sufficient doses, organic chemicals may be completely mineralised, that is converted to carbon dioxide and other non-organic species such as water.

Ultraviolet (UV) light can also be used to degrade organic chemicals in water (Rosenfeldt *et al.*, 2005; Shemer *et al.*, 2005). Furthermore, UV light is also commonly used to promote the formation of hydroxyl radicals. This can be achieved by a number of methods including by direct reaction of hydrogen peroxide (H_2O_2).

Processes which promote the enhanced formation of hydroxyl radicals are generally referred to as advanced oxidation processes (AOPs). Most commonly, AOPs for water treatment are deployed by the addition of hydrogen peroxide to ozone or UV contact chambers. The key chemical reactions for the production of hydroxyl radicals using hydrogen peroxide are:

Ozone/H_2O_2 $H_2O_2 + 2O_3 \rightarrow 2 \cdot OH + 3O_2$
UV/H_2O_2 H_2O_2 + UV (wavelength 200 to 280 nm) $\rightarrow 2 \cdot OH$

Both ozone and UV light by themselves can be used to degrade chemical contaminants to some degree. However, without the enhanced generation of hydroxyl radicals, molecular ozone or UV light alone are relatively specific in the chemical groups that they attack. Conversely, oxidation of organic chemicals by hydroxyl radicals is non-specific and all organics are ultimately susceptible if a sufficient dose is applied (Shemer *et al.*, 2006). Thus AOPs widen the range of organic chemicals that may be oxidised as well as significantly increase reaction rates (von Gunten, 2003).

The overall extent of oxidation for any AOP depends upon the contact time and the concentration of scavengers in the water (i.e. non-target oxidisable species). Typically, dissolved organic carbon (DOC) and carbonate/bicarbonate are the most important scavengers in drinking waters. High concentrations of DOC and carbonate/bicarbonate can render mineralisation of micropollutants quite inefficient and very costly (von Gunten, 2003). However, pre-treatment processes such as GAC or RO significantly reduce DOC concentrations, thus enhancing oxidation efficiency.

Advanced oxidation is often relied upon to degrade toxic chemicals which may not be well removed by RO. Two important examples are NDMA (Mitch *et al.*, 2003) and 1,4-dioxane (Zenker *et al.*, 2003).

Disinfection processes

Many of the treatment processes identified for the first two objectives are very effective for the removal of microorganisms including bacteria, protozoa and viruses. Additional processes applied specifically for disinfection therefore comprise further barriers in a multi-barrier system. Disinfection is applied after the reduction in the content of suspended and dissolved solids in order to improve the efficacy of the pathogen reduction process. Disinfection processes that have been used in AWTPs include chlorination, ozonation and UV light.

Chlorination

Chlorine is a broad spectrum disinfectant which may provide a persistent disinfecting residual in water distribution systems. This provides continuing protection against ingress of contaminants and microbial regrowth. Chlorine is commonly applied as either a gas or a hypochlorite solution. Chlorine reacts in water to produce the disinfectants hypochlorous acid (HOCl) and hypochlorite ion (^{-}OCl). The relative concentration of hypochlorous acid and hypochlorite ion depends on the pH of the water. The free chlorine content is the sum of hypochlorous acid and hypochlorite ion. Chlorine is an indiscriminate oxidant that will react with ammonia and organic matter to form chloramines and chloro-organic compounds. The sum of free chlorine and combined chlorine is a measure of the total chlorine in the system. The oxidation potential of the water decreases as chlorine is converted from free to combined form.

The efficacy of chlorine as a disinfectant will depend upon a variety of factors including the form of chlorine and the temperature and pH of the water. The disinfection mechanism depends on the type of organism (virus, bacteria or protozoan cysts). Viruses, cysts, and ova are more resistant to disinfectants than are bacteria for both free and combined chlorine. The biocidal efficacy of chlorine has been variously attributed to the reactions between chlorine and the cell wall altering cell permeability, inhibition of enzyme activity, and damaging the cell DNA and RNA. Bacteria are more susceptible to both forms of chlorine because of the high content of lipids in the cell membrane that appears to be highly susceptible.

For each organism at a given temperature and pH, the expected disinfection efficacy may be determined by the product of residual disinfectant concentration (mg/L) and contact time (min), which is denoted by a CT value (min.mg/L).

Ozonation

Ozone is a very effective bactericide and viricide and is generally believed to be more effective than chlorine. Ozone is especially effective for the inactivation of some protozoan cysts for which chlorine is relatively ineffective (Hsu & Yeh, 2003; Betancourt & Rose, 2004). Bacterial kill through ozonation is believed to occur directly because of cell wall disintegration (lysis). However, ozone is more often used as an oxidant, in combination with granular or media filtration, for the removal of synthetic and naturally occurring organics associated with taste, odour and colour problems in drinking water. Ozone was an important treatment process in the Denver DPR Demonstration Project and was included in the New Goreangab Water Reclamation Plant in Namibia (see Chapter 4).

Ozone is produced by passing dry air or oxygen between two electrodes. A high electrical potential of 10,000 to 30,000 volts is applied across the electrodes, which converts some of the oxygen to ozone. Ozone must be generated on-site and used immediately. It has a very short half-life (less than 30 minutes) under normal conditions encountered in water treatment.

Ozone is used as a disinfectant because of its efficacy against bacteria, viruses, and protozoa at low doses. Typical doses for inactivation range from 1 to 4 mg/L. Ozone can be applied at various points in the treatment train, although it is usually applied prior to coagulation or filtration. Disinfection is not significantly affected by temperatures or pH found in water treatment. The CT requirements for ozonation are significantly lower than for any other disinfectant.

Since ozone is such a powerful oxidant, it has been found to have many other uses than just for disinfection, such as iron and manganese reduction, taste and odour removal, removal of colour, improvement of downstream processes (coagulation and filtration), reduction of disinfection by-product (DBP) precursors, and increasing the biodegradable dissolved organic carbon (BDOC) in the water. In conjunction with biological activated carbon (BAC), ozone can provide a significant reduction in DBP precursors. Ozone also does not lead to the formation of chlorinated DBPs when applied.

However, ozone does form some DBPs, most notably brominated species. A higher level of bromide in the raw water may preclude many water treatment plants from using ozone. Other DBPs formed by ozonation include aldehydes and ketones.

Due to its high reactivity, ozone decays quickly and does not maintain a residual for downstream processes. Therefore, ozonation can be used as a primary disinfectant but must be followed by a secondary disinfectant (chlorine or chloramines) for effective control in the distribution system.

Ultraviolet light

The germicidal properties of UV light are due to the ability of effective wavelengths to penetrate the cell wall of a microorganism and be absorbed by the nucleic acids (components on DNA and RNA). The effect may be to either cause the death of the cell or to prevent it from replicating.

UV disinfection is generally more effective than chlorine for inactivation of most viruses, spores and cysts, however effective inactivation of some of these organisms requires relatively high doses (Metcalf & Eddy. Inc., 2003). The germicidal portion of the UV light band is about 220 to 320 nm. 'Low pressure' UV lamps generate roughly monochromatic light at a wavelength of 254 nm, which is in a very effective section of this wavelength range. Medium-pressure lamps generate polychromatic light at a number of significant wavelengths within the germicidal radiation band. While only about 7 to 15% of the output is near 254 nm, the total germicidal output can typically be 50 to 100 times that of low pressure lamps.

A UV disinfection performance validation approach adopted by the US EPA (and increasingly used in Australia) requires the validation of operating conditions including flow rate, UV intensity as measured by a UV sensor, and UV lamp status (US EPA 2006). Under this approach, the log inactivation of a challenge microorganism is measured during full-scale reactor testing for specific operating conditions of flow rate, UV transmittance, and UV intensity. The dose-response equation for the challenge microorganism (relating UV dose to log inactivation) is determined using independent, bench-scale testing. Log-inactivation values from full-scale testing are input into the laboratory derived-UV dose-response relationship to estimate the reduction equivalent dose (RED). The RED value is adjusted for uncertainties and biases to produce the validated dose of the reactor for the specific operating conditions tested. A number of manufacturers now have certified validation for commercially available UV disinfection hardware.

Advanced oxidation

Advanced oxidation processes (enhanced formation of hydroxyl radicals) are generally not relied upon for additional disinfection, above that which may be credited to UV alone. Since the half-life of hydroxyl radicals is very short, it is not possible to develop high concentrations. Disinfection management is conventionally based on the concept of microorganism exposure to a disinfectant at a specified product of concentration and time, known as the CT concept. With extremely low concentrations, the required detention times to achieve suitable CT products are prohibitive. Nonetheless, advanced oxidation using ozone and H_2O_2 appears to exhibit effective biocidal properties (Ternes *et al.*, 2003; Sommer *et al.*, 2004). Similarly advanced oxidation using UV light and H_2O_2 can achieve effective disinfection of various pathogenic microorganisms under appropriate operational conditions (Mamane *et al.*, 2007; Labas *et al.*, 2008). In particular, enhancement of UV inactivation of adenovirus by the addition of H_2O_2 has been demonstrated (Bounty *et al.*, 2012). This is significant since adenovirus has consistently been observed to be the most resistant known pathogen to UV disinfection.

Stabilisation

The objective of stabilisation is to prevent damage by corrosion to the fixtures and fittings used in the distribution system. Stabilisation techniques include pH correction with caustic or acidic solutions, and restoration of alkalinity and mineral hardness through the addition of lime. Although stabilisation follows the disinfection process, an additional chlorination step may be included to maintain a chlorine residual in the transfer pipeline.

Purification of water by reverse osmosis, and to a lesser degree, by nanofiltration results in the removal of trace minerals such as calcium and magnesium. The effect is known as demineralisation and often needs to be corrected by 'remineralisation'. This is undertaken for a number of reasons including the following:

- taste – demineralised water is considered less pleasant to consume; water with extremely low mineral content (e.g. freshly distilled water) has been described as having a 'metallic-type' taste;
- to minimise damage to soils – low calcium and magnesium concentrations relative to sodium concentrations are harmful to soils; and
- to 'stabilise' water and thus make it less 'aggressive' or 'corrosive' against a range of materials including concrete and metallic pipes.

A truly stable water is one in which the pH, alkalinity and calcium concentrations are all in equilibrium. This can be achieved but, in practice, it has been found adequate to produce water that is not fully stable, but is 'undersaturated' with respect to calcium carbonate.

The stability of the water from an AWTP may be described using a suite of indices including: The Langelier Saturation Index (LSI); the Calcium Carbonate Precipitation Potential (CCPP); and the Aggressiveness Index. These stability indices will vary as a function of the alkalinity, TDS, pH, calcium ion concentration, hardness, and temperature of the water.

The LSI is used to assess the propensity of the water to dissolve or form the alkaline scale calcium carbonate. Water that is oversaturated with calcium carbonate has a propensity to deposit scale and tends towards a positive LSI, whereas water that will dissolve scale has a negative LSI. A more reliable measure of scale formation or dissolution is the CCPP. This provides a more quantitative measure of calcium carbonate deficit or excess in water, thus giving a more accurate guide to the likely extent of calcium carbonate precipitation or uptake. Water with a positive CCPP is deemed to be scaling or protective, 0 to –5 may be described as passive (or neutral); –5 to –10 is mildly aggressive and waters below –10 are aggressive.

Addition of sodium hydroxide

Sodium hydroxide addition is effective for altering the pH, alkalinity and TDS and is used on all the Singapore NEWater plants.

Lime stabilisation

The most common approach to stabilising soft waters, that is waters that have a high proportion of sodium to calcium ions, prior to distribution is to add calcium in the form of quick lime (CaO) or hydrated lime ($Ca(OH)_2$). Using lime increases pH, alkalinity, TDS and hardness, which has a more pronounced effect on the stability indices than using sodium hydroxide. In fact, lime addition often results in a saturated solution with respect to calcium carbonate so that pH reduction is required (and thereby LSI and CCPP reduction) to prevent the precipitation of calcium salts. In order to add hardness and alkalinity without creating conditions favouring a positive LSI and CCPP, pH adjustment will be required. The common practice for pH correction following lime addition is through the addition of gaseous carbon dioxide.

The addition of gaseous carbon dioxide following lime addition will decrease the pH of the solution and prevent the precipitation of calcium carbonate by maintaining a negative LSI and CCPP in the final water.

Blending with other waters

In some seawater desalination plants, remineralisation is achieved by blending with a small proportion of seawater or the brine produced during the desalination process.

For a DPR project in which the reclaimed water is to be blended with another source prior to distribution, it may be that the blending ratio provides a suitable final mineral concentration and hence further remineralisation is unnecessary.

Examples of planned potable reuse schemes

A range of planned potable reuse schemes, employing various natural and engineered treatment processes, have been developed internationally since the early 1960s. Some of the most prominent projects are summarised in Table 1. The majority of these projects are examples of IPR schemes. However, there are four municipal DPR projects currently operating in various parts of the world. These include one in Namibia (Windhoek), one in South Africa (Beaufort West) and two in the US (Cloudcroft, NM, and Big Spring, TX).

Advanced treatment technologies utilised in each case are shown in Table 1 to indicate the additional treatment that is applied, compared to the much more common practice of *de facto* water reuse (see definition above). In all cases, these advanced treatment processes are preceded by variations of secondary or tertiary wastewater treatment. Similarly, the IPR schemes are succeeded by subsequent drinking water treatment of recycled water blended with water from environmental sources.

The potable reuse schemes included in Table 1 have employed a range of advanced treatment process to achieve various water quality objectives. While there has been some evolution in process selection over the decades, there remains no 'standard' treatment train for potable reuse. Instead, specific treatment

Table 1 Examples of planned potable reuse schemes and employed engineered treatment technologies (in addition to conventional wastewater treatment).

Project location	Project size (ML/day)	Initiation (year)	Status	Advanced treatment technologies (abbreviated)	Type of reuse
Montebello Forebay, CA, USA	165	1962	Operational	Media filtration → Cl	IPR: Groundwater recharge via soil-aquifer treatment
'Old' Goreangab Water Reclamation Plant, Windhoek, Namibia	7	1968	Superseded 2002	Clarification → DAF →sand filtration → GAC → Cl	DPR: Blending prior to treatment
Water Factory 21, CA, USA	60	1976	Superseded 2004	LC → air stripping → RO → UV/AOP → Cl	IPR: Groundwater recharge via seawater barrier
Upper Occoquan Service Authority, VA, USA	204	1978	Operational	LC → media filtration → GAC → IX → Cl	IPR: Surface water augmentation
Hueco Bolson Recharge Project, TX, USA	38	1985	Operational	LC → media filtration → O_3 → GAC → O_3 → Cl	IPR: Groundwater recharge via direct injection
Clayton County, GA, USA	66	1985	Operational	Cl → UV	IPR: Surface water augmentation via land application/wetlands
West Basin Water Recycling Plant, CA, USA	47	1993	Operational	MF →RO → UV/AOP → Cl	IPR: Groundwater recharge via direct injection
Gwinnett County, GA, USA	227	1999	Operational	UF → O_3 → GAC	IPR: Surface water augmentation
Scottsdale Water Campus, AZ, USA	53	1999	Operational	Media filtration, → MF → RO → Cl	IPR: Groundwater recharge via direct injection
Toreele Reuse Plant, Wulpen, Belgium	7	2002	Operational	UF → RO → UV	IPR: Groundwater recharge via infiltration ponds
'New' Goreangab Water Reclamation Plant, Windhoek, Namibia	21	2002	Operational	PAC → O_3 → Clarification → DAF → sand filtration → O_3/AOP → BAC/GAC → UF → Cl	DPR: Blending prior to treatment
NEWater, Bedok, Singapore	86	2003	Operational	UF → RO → UV	IPR: Surface water augmentation
NEWater, Kranji, Singapore	55	2003	Operational	UF → RO → UV	IPR: Surface water augmentation
Alimitos Barrier, CA, USA	10	2005	Operational	MF → RO → UV	IPR: Groundwater recharge via direct injection
Chino Basin Groundwater recharge Project, CA, USA	69	2007	Operational	Media filtration → SAT → Cl	IPR: Groundwater recharge via soil-aquifer treatment
Groundwater Replenishment System, Orange County, CA, USA	265	2008	Expanding to 380 ML/day	UF → RO → UV/AOP	IPR: Groundwater recharge via direct injection and spreading basins
Western Corridor Project, South-east Queensland, Australia	232	(2008)	Delayed implementation	UF → RO → UV/AOP → Cl	IPR: Surface water augmentation into drinking water reservoir
Loudoun County, VA, USA	42	2008	Operational	MBR (MF) → GAC → Cl	IPR: Surface water augmentation
Arapahoe County/Cottonwood, CO, USA	34	2009	Operational	Media filtration → RO → UV/AOP → Cl	IPR: Groundwater recharge via spreading
NEWater, Changi, Singapore	230	2010	Operational	UF → RO → UV	IPR: Surface water augmentation
Prairie Waters Project, Aurora, CO, USA	190	2010	Operational	Riverbank filtration → ASR → softening → UV/AOP → BAC → GAC → Cl	IPR: Groundwater recharge via riverbank filtration (note: the environmental buffer is used early in the treatment process).
Groundwater Replenishment Trial, Perth, Australia	5	2010	Operational	UF → RO → UV	IPR trial: Groundwater recharge via direct injection
Cloudcroft NM, USA	0.1	2011	Operational	MBR (MF) → RO → UV/AOP → UF → UV → GAC → Cl	DPR: Blending subsequent to UV/AOP
Beaufort West Municipality, South Africa	1	2011	Operational	Sand filtration → UF → RO → UV/AOP→ Cl	DPR: Blending with conventionally treated sources
Dominguez Gap Barrier, Los Angeles, CA, USA	10	2012	Operational	MF → RO	IPR: Groundwater recharge via direct injection
Raw Water Production Facility, Big Spring, TX, USA	7	2013	Operational	MF → RO → UV/AOP	DPR: Blending and then conventional water treatment

Cl = chlorine disinfection, RO = reverse osmosis, DAF = dissolved air flotation, UV = ultraviolet radiation, AOP = advanced oxidation process, UF = ultrafiltration, MF = microfiltration, SAT = soil-aquifer treatment, PAC = powdered activated carbon, GAC = granular activated carbon, O_3 = ozonation, MBR = membrane bioreactor, LC = lime clarification, IX = ion exchange.

processes have been selected on a 'fit-for-purpose' basis according to local conditions and constraints. It is clear that water quality objectives suitable for potable reuse can be achieved by a range of treatment processes with a wide variety of configurations and variations. It may be anticipated that this flexibility in design will continue as project objectives tend to be defined in terms of required treatment performances, rather than required treatment processes.

Engineered storage buffers

Depending on how a DPR system is integrated with a drinking water distribution system, there may be a practical requirement for the inclusion of an engineered (i.e. constructed) storage buffer. The purposes of such a storage buffer include:

- balancing variability between water production (supply) and water use (demand) over a set period of time (hours, days, weeks or longer);
- balancing water quality variability (unlikely to be significant with advanced water treatment systems); and
- provision of some minimum amount of time to detect and respond to process deficiencies prior to introduction to the potable supply.

Most established practices of potable reuse have relied upon the use of natural storage buffers (i.e. IPR). However, when water is treated to a high level of purity, placement into an environmental system does not necessarily result in improved water quality, and can instead expose purified water to potential environmental contaminants. Accordingly, when purified water can be produced in a system with proven performance and reliability, a relatively small engineered storage buffer, if any, may be sufficient. Important features of an engineered buffer for a DPR system have recently been proposed as (Tchobanoglous *et al.*, 2011):

- fully controlled environment;
- contained to prevent contamination and evaporative losses;
- no source of contaminants from within the buffer itself;
- ability to divert flow out of the buffer as needed;
- accommodation of monitoring and sampling equipment;
- well-characterised and optimised hydraulics; and
- high level of security.

In addition to the above features, issues relating to capacity and the provision of detention time will require careful consideration. A number of proven and conceptual engineered buffer designs have been described (Tchobanoglous *et al.*, 2011). These include above-ground tanks, covered and lined surface storage pits, enclosed subsurface storage reservoirs, engineered aquifers, and large diameter subsurface pipelines. The buffer can be a standalone facility or incorporated into the transport and distribution system, depending on site-specific factors and needs.

If an engineered storage buffer is to play a meaningful role in providing time to respond to unacceptable water quality, then the requirements of the buffer will be a function of the time required for water quality analysis and the overall reliability of the monitoring system. In this case, purified water will need to be retained in the buffer for sufficient time to verify the quality of the water prior to connection with the potable water distribution system. It will be impractical to achieve direct measurement for all regulated contaminants, but it is conceivable that a relatively small set of surrogate and indicator measures can provide effective assurance of water quality. In the event that off-specification product water was detected in the buffer, it could be diverted to an alternate discharge location or routed back into a specified point in the advanced treatment process for retreatment.

An important consideration would be the selection of appropriate surrogate and indicator measures to monitor. Essential factors to consider include capabilities for rapid or continuous monitoring and the sensitivity of the measure for indicating treatment effectiveness. Direct monitoring of pathogens in this case is unlikely to be useful since such measures tend to be neither rapid, nor sensitive for treatment performance of later barriers in a multiple-barrier system. More discussion of surrogate and indicator measures is provided in Chapter 7.

It has been proposed that a buffer storage system composed of several tanks (arranged in series or parallel) may provide a higher level of control than using a larger single storage tank (Tchobanoglous *et al.*, 2011). For example, in a system composed of four storage tanks with a monitoring system that requires 24 hours to verify water quality, one quarter of the flow could be placed into one of the tanks and held until analytical results were available.

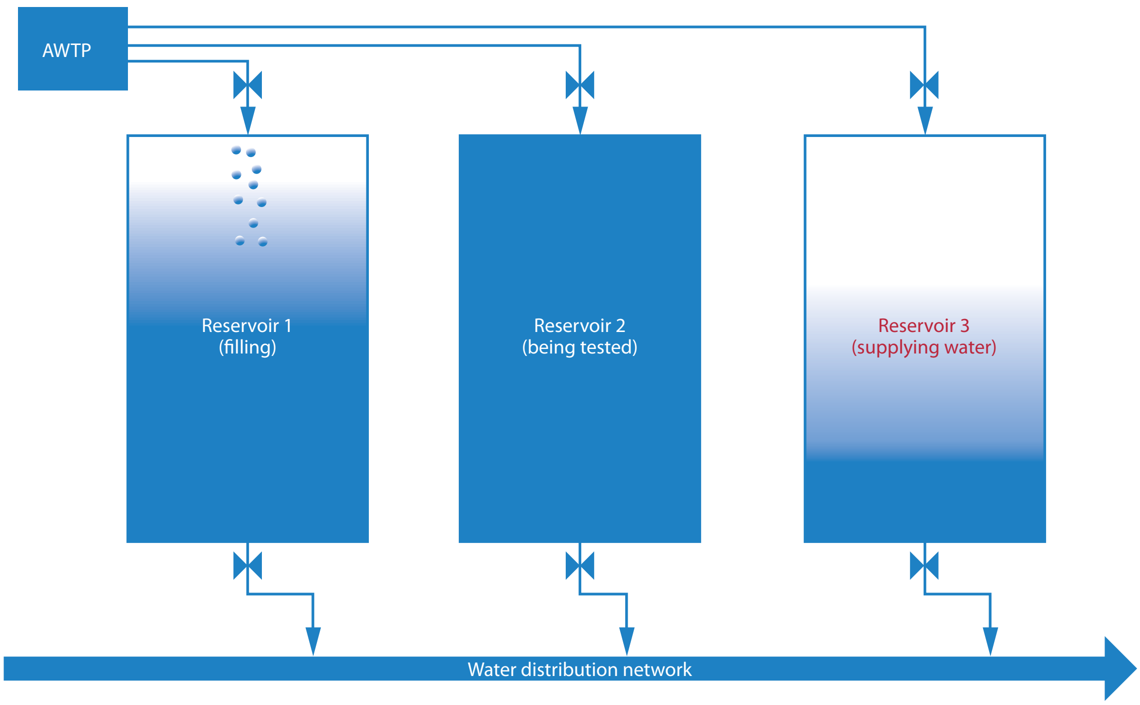
A similar concept is being considered for a proposed DPR scheme in eThekwini Municipality, Durban, South Africa (see Chapter 4). In this case, the proposed design includes three drinking water reservoirs, each holding 12 hours of water production. As one reservoir is filled, a second will be undergoing water quality testing and the third will be supplying water. This concept could technically be applied at any scale in order to achieve any required time for water quality testing. For example, if 24 hours is required, three storage reservoirs each with a capacity equal to the daily production volume of the AWTP would be required as depicted in Figure 6.

The required size for each of three reservoirs would be determined according to the following equation:

Reservoir size (kL) = AWTP daily production volume (kL/hour) x required testing time (hours)

If appropriate, the reservoirs may each be traditional elevated supply reservoirs, or feeder-tanks to a single elevated supply reservoir. Alternatively, they may be comprised of other types of engineered storage reservoirs as described above.

Figure 6 Illustration of the three-reservoirs concept to provide time for water quality confirmation.



In circumstances where supply from an AWTP can afford to be interrupted for short periods, some effective delay time may be obtained from the capacity of transfer pipelines between the AWTP and the connection with the drinking water distribution system. As an example, the Sydney Seawater Desalination plant is described in Textbox 1. In that case, a dual pipeline with a total volume of around 55 ML transfers water between the plant and the distribution system. This represents about 5 hours of potable water production from the plant. There is a capability therefore, that if water is found in this time, to have been produced of unacceptable quality, it can be backwashed through the pipeline and discharged to the sea.

In some circumstances, it may be considered that no significant storage buffer is required. Indeed, this is the largely the case for most of the existing DPR schemes (described in Chapter 4). In some jurisdictions, regulators may adopt the approach that in such cases, there needs to be confidence that operational monitoring will detect any failures in a timely fashion, before supply to consumers. That is, that reliability must be continuously measured on a 24-hour, 7-day-per-week basis.

Introduction of treated reclaimed water to a distribution system

The introduction of water to a distribution system could either be into a service reservoir or directly into a water pipeline. Direct connection with an existing water pipeline may involve a number of engineering challenges. These challenges may be exacerbated in circumstances involving the following conditions:

- blending of water sources is to be undertaken on a large scale;
- the blending ratio involves significant relative contributions from both sources;
- water demand exhibits high diurnal fluctuation, leading to variable blending ratios;
- the existing distribution infrastructure is aged and hence may feature extensive surface-deposited material and/or biofilms;
- the existing water quality involves a high or variable concentration of dissolved substances, including natural organic matter, hardness and dissolved salts; and
- the existing water source has a relatively high disinfectant demand (commonly known as 'chlorine demand').

In some cases, extensive hydraulic system modelling may be required. This would need to be undertaken under various demand and AWTP production scenarios. Outcomes from this modelling could then be used to determine:

- the areas that would receive water from the AWTP under different conditions, and in what proportions;
- velocity changes and reverse flows in distribution mains;
- pressure changes in distribution mains, including both average pressure and peak pressure; and
- the impact of AWTP production on average water age throughout the system.

These findings could then be used to assess any likely impacts on existing distribution system assets and their operation. This would enable the identification of any areas where water main breaks may occur during commissioning and optimum locations for monitoring.

The assessment of water age and chlorine demand in blended water will be of particular significance in some systems. Water from an AWTP may be chlorinated, but with a much lower chlorine demand (due to lower organic carbon composition) than other sources of water. As such, blending may affect the relationship between chlorine concentration and chlorine demand as blended water ages within the distribution system. This effect would require attention and adjustment to in-distribution system re-chlorination mechanisms.

While there are operating DPR plants that have already overcome these challenges (e.g. Big Spring in Texas and Beaufort West in South Africa), these plants are relatively small in size (up to 10 ML/day). The same challenges have been faced by a number of seawater desalination plants which also connect directly into existing water distribution systems. Perhaps the best example of a very large AWTP delivering water to an extensive and relatively old supply system is that provided by the Sydney Desalination Plant. A summary of the approach taken and lessons learnt from the commissioning of that scheme were reported by Port (2010) and are summarised in Textbox 1.

Textbox 1 Sydney Desalination Plant, NSW, Australia

The Sydney Desalination Plant supplies up to 250 ML/day of desalinated seawater to parts of Sydney. Potable water is delivered from the plant, via a 17-kilometre pipeline, directly to the city's existing drinking water distribution system. Numerous entities had roles in the planning and construction of the desalination plant and its water delivery infrastructure. These included joint ventures involved in the construction and operation of the plant, construction of delivery infrastructure, and Sydney Water, which is responsible for ongoing management of the existing distribution system.

Desalinated water is delivered to the distribution system at what is known as the 'City Tunnel', connecting a major supply reservoir ('Potts Hill') with a major pumping station ('Waterloo'). Off-take pipes along the length of the City Tunnel mean that, depending on demand, desalinated water is fed into the drinking water supply throughout much of metropolitan Sydney. Sydney Water undertook considerable planning and research to ensure that integration into the existing water network went smoothly.

System hydraulic modelling was conducted on the distribution network for a range of scenarios, including varying production rates from the desalination plant and a range of projected demand types (summer, winter, average). This modelling revealed that, depending on the volume of supply from desalination and system demand conditions, the areas that would receive desalinated drinking water and the precise blending ratios would be highly variable. In some areas, the proportion of water sourced from the plant would vary between 0 and 100% over the course of any particular day. This is due to large variations in instantaneous demand at different times of the day from the operation of pumping stations, which has the effect of moving the interface between desalination-sourced water and conventionally-sourced water up and down the length of the City Tunnel.

The modelling also showed that increases in average mains pressure would be relatively minor. It was determined that some areas close to the injection point could experience average and maximum pressure increases of 4 to 6%, but that the risk of widespread distribution main breaks was low. However, increased maximum pressure had been identified in very old sections of the network, with pipework up to 100 years old in some cases. Asset maintenance and renewal schedules were checked to verify that maintenance was up to date on pipework in these areas. Sydney Water ensured that sufficient stores of pipe sections and fittings were held in inventory at the start-up of desalination supply in case of distribution network breaks. Some system valves in the areas identified as high risk were closed to divert water through different routes and avoid the predicted increases in pressure.

Water age was modelled to determine whether the integration of desalinated water would cause a significant change to the age of water supplied in some areas, leading to differences in taste due to changes in chloramine concentration. The modelling showed that water age in some areas was predicted to fall from 11 days to 10 days. However, this change would be gradual over a period of approximately three weeks. Water age was shown to increase in other areas, from approximately 2 days to 3 to 4 days. Overall, the changes to water age and the effect on chlorine residual were considered to be minor, if any.

Velocity changes were modelled, as there was concern that significant changes may cause re-suspension of sediment or sloughing of biofilm from within distribution pipework leading to 'dirty water' complaints by customers. The modelling predicted an increase of flow velocity of 0.1 m/s in some areas close to the injection point. However, the risk of increased velocity causing water quality complaints was considered to be very low.

The drinking water specification for the desalination plant was set to closely match the existing supply in order to minimise any perceivable taste or odour changes. It was therefore anticipated that water produced by the desalination plant would have a mineral content, taste and appearance very close to that of the existing supply. Hence, any difference between the water sources was considered to be practically indiscernible by customers.

Sydney Water uses calcium carbonate precipitation potential (CCPP) to assess the propensity for water to cause corrosion or scaling. The CCPP is controlled at the desalination plant, and is specified to be in the range of –3 to –6, consistent with the rest of Sydney Water's network. However, there was concern that the pH of desalinated water could be raised by the new cement-lined delivery pipeline, due to the leaching of lime from the cement mortar lining. The pH of the desalinated water over time was monitored throughout the commissioning of the pipeline. A rise in pH caused by the pipeline was found to reduce over the course of the commissioning process. Once the pipeline was put into service it only contributed a minor rise in pH overall (approximately 1 pH unit). As a precaution, measures were put in place to reduce the residence time of water in the new delivery pipeline to minimise any pH rise.

Since the introduction of desalination was not expected to significantly change the age of water received by customers, chlorine residuals throughout the system were not anticipated to be affected. However, due to the much lower total organic carbon in the desalinated water compared to the existing supply, it was considered that decay rates of chloramine in the system may be slightly reduced. Hence, it remained important that chlorine residuals be closely monitored so that adjustments could be made either at the desalination plant or by in-distribution system re-chlorination if required.

Final commissioning of the Sydney Desalination Plant confirmed that the planning and modelling that was undertaken was highly effective in preventing any perceptible changes to water quality, infrastructure damage or customer complaints.

Chapter 3 The 'environmental buffer' of IPR – description and analysis of its role

The sole distinguishing feature of DPR relative to the more established concept of IPR is the 'environmental buffer'. The environmental buffers of IPR can be diverse, including rivers, lakes, and aquifers. However, they are all assumed to provide specific services.

In the 1990s Californian regulators used terms such as "*loss of identity*", "*travel time*", "*distance of separation*" and "*content of organics of wastewater origin*" to describe their expectations for the role of environmental buffers in IPR. These concepts were applied both to discharge to rivers upstream of drinking water intakes and groundwater recharge. In the case of groundwater recharge by percolation, additional terms such as "*vadose zone*" were used in the definition of the buffer. In the context of some of the early reservoir augmentation projects, using lakes, additional limnological terms such as "*stratification*", "*thermocline*" and "*turn over*" were applied. These terms provide insight into the expectations of environmental buffers by regulators.

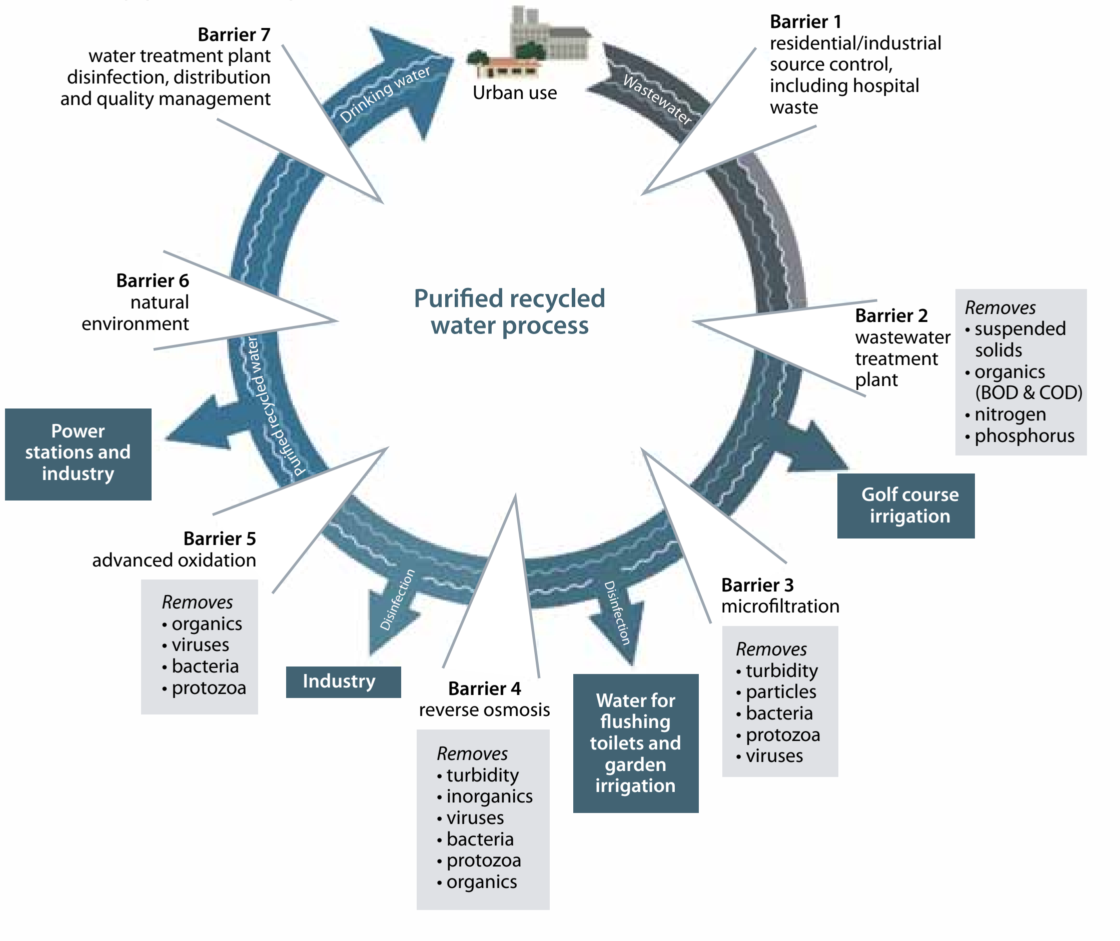
Currently, environmental buffers are perceived as one of the "*multiple barriers*" in a well-managed potable reuse project – they are part of the narrative of the "*water cycle*" and "*best practice risk management*". In 2007 the Queensland Water Commission produced a fact sheet to describe the process by which "*purified recycled water*" is "*made*" (QWC 2007). This document included the "*Purified Recycled Water Process*" as presented in Figure 7. Among the "*essential barriers to contaminants*" is Barrier 6, the "*natural environment*". The role of this barrier is described in the Fact Sheet:

> *After meeting the water quality criteria in the Australian Drinking Water Guidelines and the Australian Guidelines for Water Recycling, the purified recycled water will be blended into Wivenhoe Dam* [a major Brisbane drinking water reservoir]. *This allows the dam to act as a time and environmental buffer. Any trace amounts of chemicals that may remain after advanced water treatment will then be diluted by the large volume of water in the environmental buffer. The water is also subject to effective natural treatment processes such as biodegradation (from natural processes in the buffer) and photolysis (degradation by ultraviolet light from the sun).*

A survey of Australian stakeholders undertaken for this report, detailed in Chapter 5, revealed a diverse range of opinions regarding the purpose and effective function of the environmental buffers of IPR schemes. These included:

- to provide an additional treatment barrier for pathogenic and/or trace chemical substances;
- to provide dilution of contaminants in recycled water;
- to stabilise/equilibrate highly purified reverse osmosis permeates;
- to provide 'time to respond' to treatment malfunctions or unacceptable water quality;
- buffering the production and use of recycled water/storage;
- providing environmental outcomes/protecting water resources;
- to provide a 'perception' of increased water quality or safety/public confidence;
- to provide a perception of a disconnection between treated effluent and raw drinking water, to reduce the 'yuck factor'; and
- to demonstrate that the project is following established international practice for potable reuse.

Figure 7 The purified recycled water process including Barrier 6 (natural environment) (QWC 2007).



Environmental buffers of all IPR systems may perform each of these functions to some degree. However, given the diversity of environmental buffers, it may be assumed that their effectiveness for each role will be variable. There are currently few established standards to define performances required of environmental buffers for any of these functions. Furthermore, techniques for validating and verifying the performance of individual environmental buffers are relatively limited.

The Phase 2 Australian Guidelines for Water Recycling (NRMMC, EPHC & NHMRC 2008) were developed specifically for the management of recycled water for the augmentation of drinking water supplies (i.e. potable water reuse). These Guidelines identify the use of an environmental buffer as a key advantage of IPR compared to DPR. The document states that the advantages include:

- additional time, ranging from weeks to years;
- additional treatment, through natural processes; and
- dilution, provided that contaminant levels in the receiving water are lower than those in the recycled water.

Of these, additional time is identified in the Guidelines as “the most important”, and it is noted that “the time span is far longer than most treatment processes, which are usually completed within minutes to hours”. The Guidelines state that “indirect augmentation schemes should be designed so that the time in receiving waters is sufficient to enable operators and regulators to assess recycled water treatment and recycled water quality and, where necessary, to intervene before water is supplied to consumers”. However, this apparent requirement for IPR schemes presents a number of significant challenges.

The first challenge would be to identify what would be the minimum delay time provided by an environmental buffer in order for it to provide any meaningful additional safety compared to an analogous DPR scheme. The guidelines do not provide an answer to this question and there does not appear to be any formal answer to this question in Australia. If there were an answer, demonstrating that the system will, under a variety of flow conditions, achieve this required delay would not be a simple task. Until a suitable minimum delay time can be identified and appropriately justified, this stated advantage of environmental buffers remains somewhat arbitrary. Of course, these same questions would equally apply to an engineered storage buffer for a DPR system.

Another challenge is the need to identify what additional intervention could reasonably be achieved, beyond the further treatment that would be routinely applied, for an IPR scheme that could not also apply to a DPR scheme. It is more likely, however, that the provision of 'time to respond' would enable further water quality analysis, facilitating a more informed decision regarding whether such intervention was truly necessary or appropriate in specific circumstances.

Just as the Phase 2 Water Recycling Guidelines do not identify suitable delay times for an IPR scheme, they do not identify suitable levels of "additional treatment" or "dilution" that should be achieved in order to satisfactorily benefit from the perceived advantages of IPR compared to DPR. Indeed, the guidelines provide a range of examples of IPR schemes for which recycled water can comprise from 1% up to 80 to 90% of the water supply depending on climatic conditions.

Detention in underground aquifers has been widely accepted by Californian and Australian regulators to provide significant water quality improvements. However, neither regulator has assigned microbial treatment credits to the additional treatment provided by surface water environmental buffers. Reasons for this include that these values tend be difficult to quantitatively validate and verify, and that they are often highly variable, being subject to seasonal in-flow, temperature and demand conditions. Instead, regulators have tended to consider any additional treatment afforded to surface water environmental buffers as 'a bonus' on top of the validated and verified engineered treatment performance.

Subsurface treatment leading to groundwater augmentation

The Montebello Forebay spreading grounds in Los Angeles County began operation in 1962, representing the oldest planned IPR project in the US. It is jointly operated by the Water Replenishment District of Southern California and the County Sanitation Districts of Los Angeles County.

The spreading grounds are used for flood control, storm water conservation, and aquifer recharge using imported surface water, stormwater, and reclaimed water. Dechlorinated tertiary treated effluent from three WWTPs is diverted to a series of recharge basins along the Rio Hondo and San Gabriel rivers. The spreading operations are characterised by a shallow vadose zone of approximately 10 m. Currently, the contribution of reclaimed water to recharging the local groundwater is limited to 35%. The reclaimed water blends with groundwater in the aquifer and remains underground for approximately 6 months before it is collected in drinking water wells in the Central Groundwater basin.

Since this pioneering project, subsurface treatment for reclaimed water has been employed with various modifications, such as rapid infiltration basins, vadose zone injection wells, infiltration trenches, and riverbank filtration.

Recharge basins are often located in, or adjacent to, floodplains characterised by soils with high permeability. To maintain permeability, recharge basins are usually operated in wetting and drying cycles. As the recharge basin drains, dissolved oxygen penetrates into the subsurface facilitating biochemical transformation processes, and organic material accumulated on the soil surface dries allowing for the recovery of water infiltration rates. In riverbank filtration, constant scour forces due to stream flow prevent the accumulation of particulate and organic matter in the infiltration layer.

Various qualities of reclaimed water have been used in recharge operations, ranging from primary effluents to highly treated water. The Orange County Water District in Fountain Valley, California, is applying reclaimed water to surface spreading basins that has been treated with RO and advanced oxidation processes.

The attenuation processes that have been attributed to subsurface systems include transformations of organic matter, oxidation/reduction (redox) reactions, nitrogen transformations, and inactivation of pathogens. The degree of water quality changes will depend on the quality of feed water applied to recharge operations.

The removal of organic matter during infiltration can be highly efficient and largely independent from the level of above-ground treatment, since biodegradable organic carbon that is not attenuated during wastewater treatment is readily removed during groundwater recharge (Rauch-Williams & Drewes, 2006).

However, the removal of easily biodegradable organic carbon in the infiltration zone usually results in depletion of oxygen and the creation of anoxic conditions due to the action of microorganisms. While this transition is advantageous regarding denitrification processes, it may also lead to the solubilisation of manganese, iron, and arsenic from native aquifer materials. If these interactions occur, an appropriate post-treatment process is required after recovery of the recharged groundwater to remove heavy metals. Dissolved ammonium can be effectively removed by cation exchange onto soil particles during wetting cycles, followed by nitrification of the adsorbed ammonium during drying cycles. Nitrate is not adsorbed to soils and, providing sufficient carbon is present to create anoxic conditions, can be denitrified during subsequent passage through the subsurface (Fox *et al.*, 2001). Given the high carbon demand for denitrification, reclaimed water with high nitrate concentrations is generally not applied to groundwater recharge.

The combination of filtration and biotransformation processes during subsurface treatment can be very efficient for the inactivation of pathogens, especially viruses. From an extrapolation of tracer data derived from a full-scale recharge basin study in the Montebello Forebay, California, a 7-log reduction of bacteriophage is expected to occur within approximately 30 m of subsurface travel (Fox *et al.*, 2001). In 2002 and 2003, a historic drought significantly affected the city of Aurora, Colorado. The city was faced with the short-term prospect of rationing water and a long-term unsustainable water resource portfolio in view of significant population growth. The city owns trans-basin water rights from resources located on the western slope of the Rocky Mountains. Therefore, they decided to recover these resources from the South Platte River, downstream of Denver, Colorado.

The South Platte River receives treated wastewater effluents and runoff from the Denver/Aurora metropolitan area. Of the wastewater treatment plants discharging to the river, the Denver Metro WWTP discharges approximately 600 ML/day, which makes up a significant portion of the river's (up to 60% annually). The city considered several different options for the recovery of this water and settled on a combination of natural purification systems with advanced engineered treatment processes to establish a project that would increase Aurora's drinking water supply by 20%.

The natural purification system, using a combination of riverbank filtration wells and artificial recharge and recovery basins, is located along the South Platte River approximately 30 km downstream of Denver. This provides a hydraulic retention time of approximately 30 days in the subsurface system, removes particulate matter and pathogens, decreases total organic carbon concentrations from 6 to 11 mg/L in the river to 3 to 4 mg/L, achieves nitrification/denitrification with nitrogen concentrations of less than 2 mg N/L, and substantial reduction of trace organic chemicals. Three pump stations and a 56 km pipeline lift the recovered water from the natural purification system and convey it to a drinking water treatment plant located at one of the city's current conventional sources. This scheme is somewhat unusual as a planned IPR project since the environmental buffer is positioned relatively early in the overall treatment process.

Direct injection into a potable aquifer

Direct injection of reclaimed water into a potable aquifer was pioneered in Orange County, California with the establishment of Water Factory 21 in 1976. This project represented the precursor and benchmark for several subsequent IPR projects, including the Hueco Bolson Recharge Project in El Paso, Texas (1985), the West Basin Water Recycling Plant, California (1995) and the Scottsdale Water Campus, Arizona (1999).

The Groundwater Replenishment System in Orange County, California, was constructed to supersede Water Factory 21. It was completed in 2008 with a capacity of 265 ML/day, representing the largest potable reuse project worldwide. Approximately half of the reclaimed water provided by this facility is applied to surface spreading basins, and the remainder is used to maintain injection wells of the Talbert Gap Barrier to protect an important groundwater aquifer from seawater intrusion by the Pacific Ocean.

Some biological and physical attenuation processes have been shown to be very efficient in subsurface environments (Amy & Drewes, 2007). However, variable requirements exist regarding the minimum retention time of reclaimed water in an environmental buffer prior to extraction. For example, Washington State water reclamation and reuse standards require that "reclaimed water shall be retained underground for a minimum of 12 months prior to being withdrawn as a source of drinking water supply" (WSDH & WSDE 1997). The more recent Californian Draft Regulations: Groundwater Replenishment with Recycled Water are considerably more complex in their requirements, but in some cases allow underground retention times of as little as two months (CDPH 2013). These Californian draft regulations also specify anticipated levels of removal of some pathogenic substances and minimum dilution requirements with ambient groundwater. Others have defined minimum set-backs (i.e. horizontal separation) between reclaimed water injection and potable wells.

The Phase 2 Australian Guidelines for Water Recycling include a module dedicated to managed aquifer recharge (NRMMC, EPHC & NHMRC 2009a). Consistent with the broader approach to water quality management in Australia, these guidelines tend not to be prescriptive in terms of factors such as underground residence times, but instead require an individual risk assessment and risk management plan for all projects. This approach is supported by evidence cited in the guidelines that pathogen and chemical attenuation in aquifers is influenced by factors including the pathogen or chemical type, recharge water source, temperature, redox state and oxygen concentrations, activity of indigenous groundwater microorganisms, and aquifer geochemistry. Default attenuation rates for selected pathogens and chemicals are provided in the guidelines. But, most importantly, the guidelines state that individual scheme validation must be achieved:

> *The information provided on attenuation rates is specific to the site, and should be regarded as only indicative in designing schemes. The attenuation rates for pathogens and chemicals must be validated specifically for each scheme. Validation is the body of scientific evidence that demonstrates the capability of the attenuation zone in the aquifer. It must also demonstrate that the process control and operational monitoring provide ongoing assurances that the attenuation zone is operating effectively and is producing water of an appropriate quality,*

From November 2010 through to December 2012, Water Corporation (Western Australia) undertook a comprehensive Groundwater Replenishment Trial as a means of assessing the possible future use of managed aquifer recharge for the city of Perth. An AWTP (UF/RO/UV) was constructed and validated at the Beenyup WWTP in the northern suburbs of Perth during 2009 and 2010. This plant has a production capacity of 5 ML/day of reclaimed water, which was used to recharge an important drinking water aquifer (known as the 'Leederville Aquifer') by direct injection throughout the two-year trial (Water Corporation, 2013). Reclaimed water for the Groundwater Replenishment Trial was recharged into the aquifer 120 to 220 metres underground at a location remote from any drinking water abstraction wells.

Following the successful completion of the Groundwater Replenishment Trial, the Western Australian Government announced that groundwater replenishment would become the next climate independent water source to secure Perth's drinking water supply (Redman, 2013). Pending approvals, the initial stage of Australia's first full-scale groundwater replenishment scheme will have the capacity to recharge 7 billion litres of recycled water annually, and is planned to begin operation by mid-2016. The scheme will ultimately deliver up to 28 billion litres per year by 2022.

Surface water augmentation

The pioneering IPR project to use surface water augmentation in the USA was led by the Upper Occoquan Service Authority (UOSA) in Virginia. Motivated by population growth, increasing urbanisation, and a declining water quality of the Occoquan Reservoir, the major raw water supply for northern Virginia, the UOSA water reclamation system was established in 1978. The current water reclamation facility has a capacity of 200 ML/day.

Reclaimed water from the UOSA facility is discharged into a tributary of the Occoquan Reservoir. The discharge point is approximately 10 km upstream of the headwaters of the reservoir and 30 km upstream of the drinking water supply intake. Reclaimed water typically accounts for less than 10% of the annual average inflow to the reservoir, but during drought conditions may account for up to 90%.

Singapore began practising surface water augmentation for IPR in 2003 with construction of two AWTPs at Bedok and Kranji. Since then, additional plants were constructed at Seletar in 2004 (decommissioned in 2011), Ulu Pandan in 2007 and Changi in 2010. The Singapore Public Utilities Board (PUB) has branded the reclaimed water produced from these plants as 'NEWater'. The treatment train employed at each of them is based on micro- or ultra-filtration, reverse osmosis and UV disinfection. NEWater is supplied to silicon wafer fabrication plants for production of ultra-pure water, where the water quality requirements are more stringent than for drinking. NEWater is also supplied to electronics and power generation industries as well as commercial and institutional complexes for cooling purposes. During dry periods, some 110 ML/day of NEWater are used to replenish surface water reservoirs prior to conventional drinking water treatment with an annual average of 30 to 40 ML/day. Together, Singapore's four NEWater plants can meet approximately 30% of the nation's (potable and non-potable) water needs. By 2060, Singapore PUB plans to expand capacity so that NEWater can meet up to 55% of projected future demand.

The Western Corridor Recycled Water Project (WCRWP) was constructed in South-East Queensland, Australia, during 2007–08. The WCRWP has the capacity to produce up to 230 ML/day, which represents approximately 30% of the total current water supply needs for South-East Queensland. The WCRWP was designed to use treated effluents from six wastewater treatment plants to produce reclaimed water in three advanced water treatment plants suitable for both industrial and potable uses. The scheme is designed to partially supplement potable water supplies by adding highly treated reclaimed water into South-East Queensland's largest drinking water reservoir, Lake Wivenhoe. After mixing with water from environmental sources, the blended reclaimed water would be further treated at the existing potable water treatment plant located at Mt Crosby. Drinking water would then be distributed via the existing supply network.

Comprehensive validation and verification testing during piloting and start-up of the facilities has been conducted. These activities demonstrated that the reclaimed water quality meets, and even exceeds, the requirements of the Phase 2 Australian Guidelines for Water Recycling (NRMMC, EPHC & NHMRC 2008) as well as the *Australian Drinking Water Guidelines* (NHMRC & NRMMC 2011). However, due to uncertainties relating to methods for validation of the environmental buffer performance, the full scheme performance requirements and validation were applied at the AWTPs. That is, it was necessary to demonstrate that the engineered processes could meet the required quality standards without any assumed contribution from the environmental buffer. As such, any additional treatment benefit from environmental buffer is assumed to provide an unquantified level of 'treatment redundancy', implying an additional level of safety were the engineered treatment processes to fail or underperform.

Following extensive rainfall in 2009, reservoir levels in Lake Wivenhoe recovered to more than 60% of capacity. At that time, a political decision was made that augmentation of Lake Wivenhoe with reclaimed water need only occur once the reservoir storage levels fall below 40% of capacity. Water produced from the WCRWP is currently supplied directly to major industrial users including the Swanbank and Tarong Power Stations that previously drew water from the Lake Wivenhoe system.

Chapter 4 International activities related to DPR

International interest in DPR as a component of water supply management has been rapidly increasing in recent times. In particular, the US and South Africa have begun developing new DPR schemes during the past five years. This renewed interest has been accompanied by a growing body of documentation – most notably from the US – outlining some of the key drivers and obstacles, and clearly working towards a path for future implementation on a wider scale.

Notable examples of international experience with municipal DPR schemes are described in this chapter. This is followed by a summary of key documents from the US, revealing a chronology of increasing realisation of the importance of DPR as a future water resource management strategy.

International experience with municipal DPR schemes

Throughout most of the past few decades, the discussion of potable water reuse in Australia was almost exclusively focused on IPR, often accompanied by the statement that there was only one operational DPR scheme in the world. This was a reference to the – indeed pioneering – Goreangab Water Reclamation Plant in Windhoek, Namibia. However, that picture has begun to change with three more operational projects in South Africa and the US during the past five years.

Goreangab Water Reclamation Plant, Windhoek, Namibia

Since 1968, the City of Windhoek in Namibia has pioneered DPR with the commissioning of the Goreangab Water Reclamation Plant. The history of this project, and ongoing developments, have been written about intermittently by a number of authors including Haarhoff and Van der Merwe (1996), du Pisani (2006), Lahnsteiner and Lempert (2007) and Van der Merwe *et al.* (2008).

Namibia is located in the south-western part of Africa and is the most arid country south of the Sahara Desert. Windhoek is the capital and largest city in Namibia, located in the centre of the country. The city is situated on the Khomas Highland plateau, at about 1700 metres above sea level. This arid location is 300 km from the ocean and 700 km from the nearest perennial river. The population of Windhoek is about 350,000 and continues to grow due to migration from other parts of Namibia.

Historically, Windhoek had relied on groundwater to supply the city's needs. Since the 1930s two small surface water reservoirs were created by damming ephemeral rivers. The second of these was Goreangab Dam, constructed in 1958. A conventional water treatment plant was also constructed to treat the water to potable standards (du Pisani, 2006). However, the water supply to the Goreangab Water Treatment Plant was found to be limited and unreliable.

In 1968, the Goreangab water treatment plant was converted so as to able to treat effluent from the city's Gammams Wastewater Treatment Plant as an additional source to the Goreangab Dam. The plant was thus renamed the Goreangab Water Reclamation Plant, treating municipal wastewater effluent blended with raw surface water, with an initial capacity of around 4 ML/day. Because the whole city, as well as its informal settlements, lies within the catchment area of the Goreangab Dam, the water from the reservoir is said to be often of lower quality than the municipal wastewater effluent. The initial Goreangab Water Reclamation Plant, now called the 'Old' Goreangab Water Reclamation Plant, was upgraded several times with the last upgrade undertaken in 1997 and an ultimate capacity of around 7 ML/day.

During eight years of water shortages between 1968 and 2000, the Old Goreangab Water Reclamation Plant produced at least 12% of the total potable water supply to Windhoek, with production peaking in 1997 with 18% (3 GL/year) of the total demand.

During the early 1990s, it was determined that additional capacity and improved water quality would be required in the future. A new plant, known as the New Goreangab Water Reclamation Plant (NGWRP) was then completed in 2002, on a site adjacent to the old plant. The NGWRP has a capacity of around 8 GL/year, able to provide up to 35% of the total water supply on an ongoing basis and up to 50% during severe drought conditions.

The plant design philosophy of the NGWRP follows the multi barrier concept. The treatment train consists of coagulation/flocculation, followed by dissolved air flotation and media filtration. The water is subsequently treated by ozone/hydrogen peroxide followed by biologically active granular activated carbon filtration. A final barrier is provided by ultrafiltration prior to final stabilisation and chlorine disinfection. A simplified process flow diagram for the NGWRP is provided in Figure 8.

The concept of source control was also incorporated into the Goreangab project by collecting and treating industrial sewage separately for irrigation reuse (Van der Merwe *et al.*, 2008). Thus, predominantly municipal and commercial wastewater is used to augment the potable water supply.

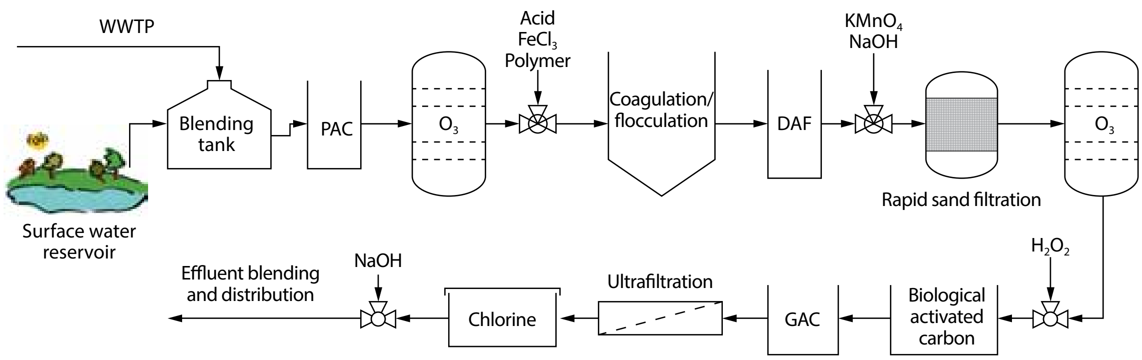
Treated water quality is subject to ongoing monitoring and testing. Windhoek has managed to overcome negative public perception with positive and proactive marketing providing a viable option for innovative integrated water resource management.

Denver's Direct Potable Water Reuse Demonstration Project, USA

A potable water reuse demonstration project was initiated in Denver, Colorado, in 1985 (Lauer, 1993) and assessed over a 13-year period. This project's purpose was to examine the feasibility of upgrading secondary treated effluent to a potable quality that could be piped *directly* into the drinking-water treatment system. An advanced water treatment plant was constructed with a capacity to treat 4 ML/day of unchlorinated secondary effluent from the Denver wastewater treatment plant.

During the first three years a number of alternative processes were evaluated in order to select an optimum treatment sequence which would then be subject to a two-year animal feeding health-effect study (Lauer *et al.*, 1990). The selected advanced treatment processes included high-pH lime treatment, single- or two-stage recarbonation, pressure filtration, selective ion exchange for ammonia removal,

Figure 8 Process flow diagram for the New Goreangab Water Reclamation Plant .



two stage activated carbon adsorption, ozonation, reverse osmosis, air stripping, and chlorine dioxide disinfection (Lauer *et al.*, 1991). The process flow diagram is presented in Figure 9.

Analytical studies compared the water produced by the plant to existing drinking-water standards and to Denver's current potable supply. The recycled water equalled or exceeded the quality of Denver drinking water for all chemical, physical and microbial parameters tested except for nitrogen, and alternative treatment options were subsequently demonstrated for nitrogen removal (Rogers & Lauer, 1992). Furthermore, the recycled water quality exceeded all state and federal standards for definable constituents.

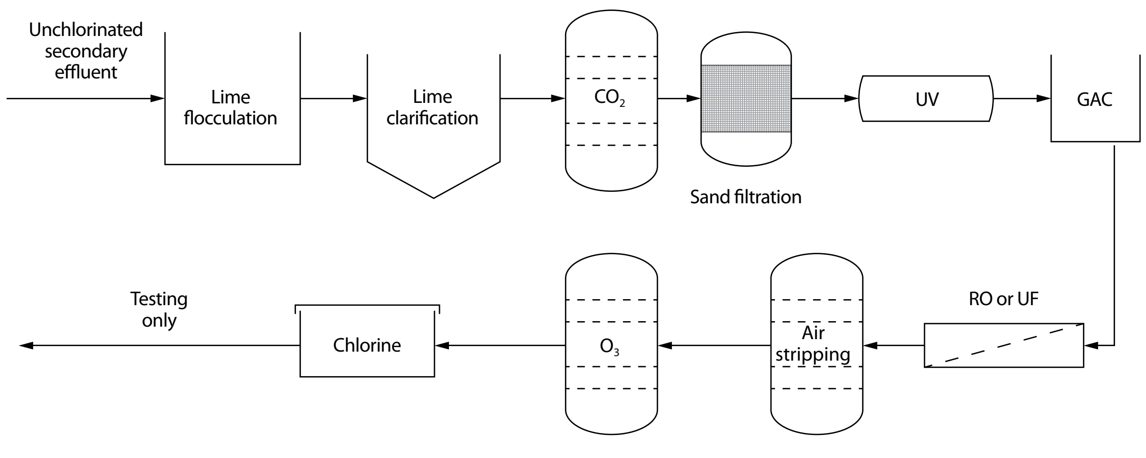
A two-year health effects study using rats was undertaken to investigate any chronic toxicity and tumour-formation effects of the reclaimed water (Condie *et al.*, 1994). These tests were conducted using reclaimed water samples concentrated 150 and 500 times. Denver's current drinking water was used as a negative control since it is derived from a relatively protected source.

A test cohort of 140 rats (70 male, 70 female) were fed with concentrates of either conventionally sourced drinking water, reverse osmosis reclaimed water or ultrafiltration reclaimed water. An additional 140 rats were fed distilled water and served as the control group. The parameters evaluated in this study included clinical observations, survival rate, growth, food and water consumption, haematology, clinical chemistry, urinalysis, organ weights, gross autopsy, and histopathological examination of all lesions, major tissues and organs.

The incidence and types of clinical indications were comparable in all groups of the same sex. There were numerous statistically significant differences between control and treated groups in weekly measurements of body weight, food consumption and water consumption, but all of these were minor and not consistent with treatment groups throughout the study. Therefore the differences were not considered to be treatment related. There was a decrease in survival rates in some of the male treatment groups. The toxicological significance of this finding was unknown since there was no similar decrease in survival in the female treatment groups. Furthermore, there was no decrease in survival rates in any male or female treatment group in a parallel mouse study.

Clinical pathology, gross pathology and microscopic pathology did not reveal any findings that could be considered treatment related. The variety, frequency and severity of spontaneously occurring incidental lesions and neoplasms were within the anticipated range for the age and strain of rat. There was a higher incidence of thyroid 'C' cell adenoma in a group of male rats fed conventional drinking-water concentrates. However, this higher incidence was reported to have been well within the historical range anticipated for this type of neoplasm.

Figure 9 Process flow diagram for the Denver DPR Demonstration Project.



The authors concluded that the administration of RO-treated reclaimed water, UF-treated reclaimed water or Denver's present drinking water at up to 500 times the concentration of the original water samples over an extended period of the animal's life expectancy did not result in any demonstrable toxicological or carcinogenic effects. On the basis of this study, as well as the parallel chronic mouse study and a two-generation reproductive study, it was concluded that the application of advanced water treatment process to a secondary treated effluent can produce water that may be safely used as a source of drinking water for public consumption.

Cloudcroft, New Mexico, USA

Cloudcroft, New Mexico, is a village located within the Lincoln National Forest. It has a permanent population of less than 1000, but this increases to more than 2000 during weekends and holidays due to its popularity as a snow skiing destination. At 2600 m, Cloudcroft is among the most elevated populated locations in the US.

The principal potable water sources in Cloudcroft include groundwater springs and wells. However, due to reduced flow during drought conditions, additional potable supplies have had to be imported using water tankers on weekends. Recognising the need for a long-term alternative, a DPR project was constructed and began operating in 2011.

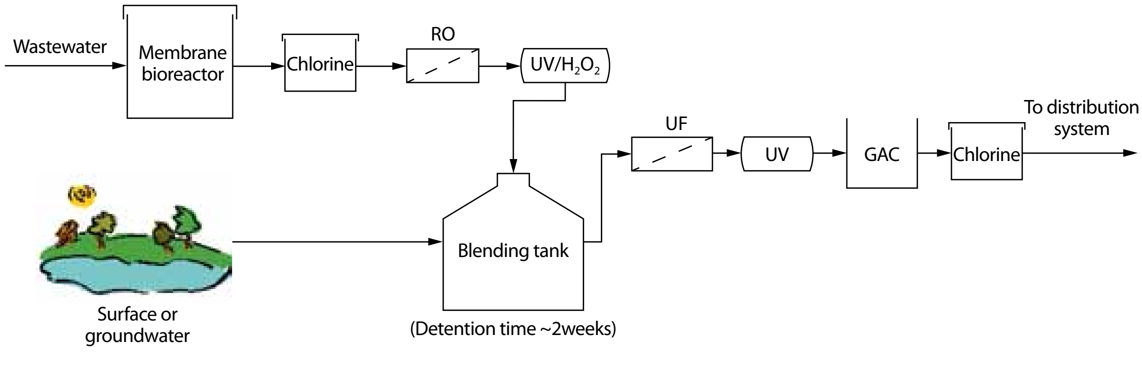
The Cloudcroft DPR project involves blending highly treated reclaimed water with a slightly greater volume (51%) of spring water and/or well water. The blended water is placed in a storage reservoir or 'blending tank' with a detention time of about two weeks. Water from the storage reservoir is then further treated before being pumped into the drinking water distribution system. It has been reported that blending the highly treated water with natural water allowed the health authorities to define the process as "indirect potable reuse" (Tchobanoglous *et al.*, 2011). However, this scheme has since been widely recognised as an example of DPR. The process flow diagram for the project is presented in Figure 10.

Big Spring, West Texas, USA

Big Spring is a city in West Texas. It is located in the Permian Basin, with a population of approximately 30,000 people. The Permian Basin has been subjected to severe drought conditions during much of the past 15 years. Water supply servicing to Big Spring is provided by the Colorado River Municipal Water District (CRMWD). Most of the water supplied is raw surface water from three reservoirs constructed on the Colorado River. These sources are supplemented by groundwater reserves, but in the early 2000s it was apparent that additional supplies would be needed to meet growing demand and to offset apparent reductions in reservoir yields.

The Big Spring WWTP is located east of Big Spring, and is permitted to treat up to 14 ML/day of municipal wastewater. It was identified that The Big Spring WWTP effluent could be used in several ways

Figure 10 Process flow diagram for Cloudcroft DPR project.



to augment or offset potable water demand in Texas. The principal categories considered included direct non-potable irrigation, direct non-potable industrial use, as well as both IPR and DPR (Sloan & Dhanapal, 2007). Several factors persuaded the CRMWD to pursue potable reuse, including (Sloan, 2011):

- non-potable reuse demands tend to be highly seasonal, limiting the overall volume saved from reuse facilities. Potable reuse represents a continuous demand;
- few large potential customers were available for non-potable reuse;
- low-density development in the area meant that transmission distances for distributed non-potable reuse would be significant and distribution systems expensive;
- arid conditions have restricted landscape irrigation, reducing potential demand;
- high concentrations of dissolved solids in the wastewater effluent limited reuse opportunities unless desalination (reverse osmosis) was included; and
- current raw drinking water sources and other prospective sources are generally distant and lower in elevation than customers, resulting in high delivery costs, while reclaimed water is already local.

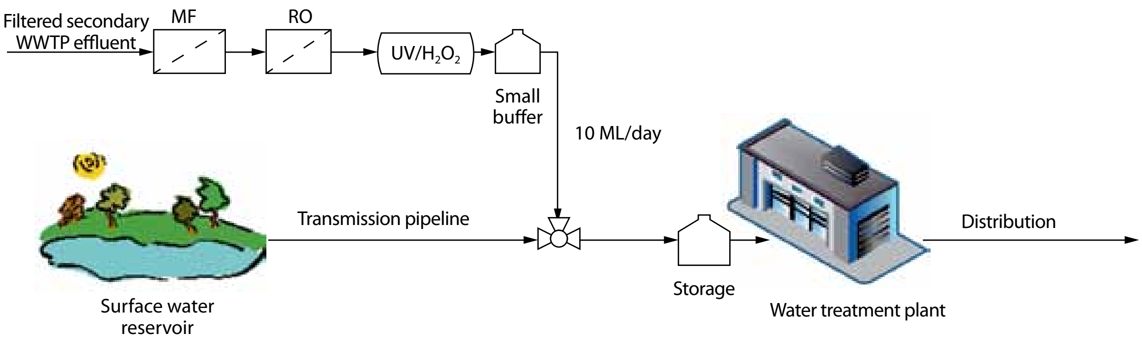
It was recognised that blending reclaimed water with raw drinking water offered the opportunity for year-round use, reduced transmission distance and an improvement in raw water salinity. Several locations in Texas have developed plans for indirect potable reuse. However, IPR was not considered to be as well suited to the Permian Basin area, due to high evaporative losses and the salt concentrations in both the current surface water and in available effluent sources.

Salt removal by reverse osmosis was deemed a necessary step for large-scale water reclamation. With this level of treatment came the opportunity to shorten the reuse cycle. The CRMWD's network of long-distance, large diameter pipelines presented a convenient means of blending high quality reclaimed water with other sources and conveying the blended product to their customer cities.

The implemented DPR project intercepts filtered secondary effluent from the Big Spring WWTP and transfers it to an adjacent site, where advanced treatment is provided. The AWTP consist of microfiltration, reverse osmosis and UV/H_2O_2 advanced oxidation, with capacity to produce up to 7 ML/day. This water is then blended with raw surface water in the CRMWD's water transmission pipeline as shown in Figure 11. Project construction began in June 2011, with blending operations having begun in April 2013.

Reclaimed water now contributes up to 15% of the blended water in the existing pipeline network supplying CRMWD's member and customer cities including Big Spring. These cities operate conventional surface water plants which will continue to provide final treatment, including disinfection, prior to drinking water distribution to customers.

Figure 11 Process flow diagram of the Big Spring DPR scheme.



The advanced treatment processes used in this reclamation project require significant energy to produce a high quality product suitable for blending. However, the designers of this project have considered this in the context of the energy requirements of existing supplies and other potential supplies (Sloan, 2011). It was estimated that the MF and RO treatment would use about 13 kWh of energy per 1000 litres of water produced (13 kWh/kL). UV oxidation was estimated to require an additional 1.5 kWh/kL and pumping to and from the reclamation facility would increase the total to about 20 kWh/kL reclaimed water.

By comparison, lifting water from the existing reservoir (Lake Spence) to Big Spring requires about 16 kWh/kL under normal conditions. Currently the water level in the reservoir is so low that a barge mounted pump station is required to lift water into the permanent intake structure. The power consumption for the barge operation is not readily available, but it is apparent that lifting water to Big Spring requires almost as much energy as treating and pumping effluent from the wastewater treatment plant (Sloan, 2011). The CRMWD currently uses about 3 kWh/kL to pump effluent from the WWTP away from the Colorado River to protect drinking water supplies. Each litre reclaimed therefore represents a litre of avoided effluent pumping. Adding this to the normal raw water pumping requirement from Lake Spence yields a total of 19 kWh/kL of avoided energy, comparable to the energy requirement for the total reclamation process.

In terms of engineered storage buffers, the AWTP includes about 2 ML of product water storage, which represents 6 to 7 hours at full production. After blending and prior to potable water treatment, the water is transferred to a 60 ML balancing reservoir. This is an open, earthen reservoir, which was constructed to allow mixing and equalisation for a number of raw water sources at a strategic junction in the system. It was in place long before the reclamation project was conceived, and although it does represent storage and potential delay before proceeding to final treatment and distribution, it is not monitored or controlled for that purpose. There also are no test results which are required to allow the reclaimed water to be released. The CRMWD relies upon continuous filtrate turbidity and RO permeate conductivity to confirm the quality of the treated water, supplemented by air pressure tests of the membrane filtration and continuous monitoring of the UV disinfection system.

Further developments in Texas, USA

Following the development of the Big Spring project, a number of other DPR projects are currently under consideration or development in Texas. The Texas Commission on Environmental Quality (TCEQ) is responsible for approving potable reuse projects in the state and has now provided approval for a number of DPR projects.

A project proposed for the City of Wichita Falls is currently in the most advanced stages of planning. In mid-2013, Wichita Falls was under drought emergency conditions with the major surface water supply (Lake Arrowhead) at less than 35% of capacity. In response, the city has developed a two-phase approach to potable reuse. The long-term objective is an IPR scheme that involves returning advanced treated effluent from Wichita City's 'River Road' WWTP to Lake Arrowhead. However, this project requires the securement of a discharge permit from the TCEQ, which the city estimates will take four to five years to obtain. If the drought does not break in the meantime, Wichita Falls City intends to implement a temporary 'emergency' DPR project.

The proposed Wichita Falls DPR project involves taking effluent from the River Road WWTP and delivering it to an AWTP located at the existing Cypress Water Treatment Plant, where the water would undergo treatment by MF and RO. It would then be discharged to an engineered holding lagoon, where it would be blended with surface water from Lake Arrowhead at a ratio of approximately one-to-one. The blended water would then be treated by conventional drinking water treatment processes at the Cypress Water Treatment Plant. The City estimates that this project could be in place and operational by early 2014.

In 2013 the TCEQ also provided conditional approval for a proposed DPR project for the City of Brownwood, West Texas. The City of Brownwood purchases treated drinking water from Brown County Water Improvement District #1, which sources water from Lake Brownwood. In recent years, drought conditions have placed considerable pressure on this supply, leading to high level water restrictions. A DPR project utilising treated effluent from the City of Brownwood WWTP is proposed as a solution to the water shortage. This water would be treated by UF followed by RO and UV disinfection at what is known locally as the 'Supplemental Water Supply Treatment Facility'. If constructed, this facility would provide around 5 ML/day of potable water, representing up to a third of the city's needs.

Potable water is currently delivered to the City of Brownwood by a single supply pipeline. This situation is seen to exacerbate the city's water supply vulnerability. The City of Brownwood Division Director of Public Works, David Harris, commented on this at a 2012 Council Meeting. He explained that in addition to increasing available water supply, the proposed DPR project would afford the city a degree of water security independence and resilience against extreme weather events (Tipton, 2012):

> *We have no other supply of water without this plant. This is very important should something drastic happen to the water improvement district. A tornado is our biggest vulnerability. If Brown County loses their treatment plant, we have about 24-48 hours of water and then we are out of water...It would shut down schools, businesses and everything else. This will give us the amount of water to where we can keep going, the public would be notified, we would shut down as much as possible and we would be able to maintain a water supply to meet normal function of life.*

As of July 2013, city officials hadn't formally decided whether to move forward with construction of the plant. While finalising design plans, the city is also considering an alternative water supply augmentation plan based on drilling four to six wells to access groundwater from deep aquifers. Competition for the existing water supply between the city and commercial irrigators also appears to be a contentious community issue.

While details are currently scant, it has been reported that a number of other cities in Texas are also in the early stages of considering the potential advantages of DPR projects. These include the cities of Abilene and Lubbock.

Beaufort West Municipality, South Africa

Beaufort West Municipality is situated in central Karoo, one of the driest areas in South Africa. It functions as the economic, political and administrative centre of central Karoo. There are roughly 40,000 inhabitants in Beaufort West Municipality spread across three towns, one of which is Beaufort West.

In 2010, a severe drought nearly depleted the town's raw water sources, resulting in an immediate shortage of drinking water. By January 2011, the town was relying on trucks delivering additional drinking water to support its inhabitants. At that time, 5 litres of drinking water per person per day were being trucked to more than 8000 homes. Frequent droughts in combination with predicted population growth and large informal housing areas that are yet to be connected to the water supply system are expected to increase the pressure on raw water sources in future.

The situation in Beaufort West led to the construction of a DPR plant known as the Beaufort West Water Reclamation Plant (BWWRP). The approach was conceived by the Beaufort West Municipality Director of Engineering Services, Mr Louw Smit. The plant was constructed as a 'design, build and operate' project with local contracting firm 'Water & Wastewater Engineering' (Marais & von Durckheim, 2012). It was commissioned in January 2011 and has been providing reliable, quality drinking water since.

Subsequent to conventional tertiary treatment, the additional treatment processes used at the BWWRP include UF, RO, UV/H_2O_2 advanced oxidation and final chlorination. The plant is designed for a capacity of 2.1 ML/day. The reclaimed water is pumped to a 4.5 ML service reservoir 4 km away at a relative elevation of 100 m. The municipality has three service reservoirs on the hill. The treated reclaimed water is fed into 'Reservoir 1'. The municipality feeds conventionally sourced water (conventionally treated dam water and borehole water) to 'Reservoir 3'. In both instances the water is required to comply with potable water standards. The municipality then blends approximately 20% reclaimed water and 80% conventionally sourced water into 'Reservoir 2'. This mixed water is then distributed to the town. Residual chlorine adjustment is provided as the water leaves Reservoir 2 to supply the town. A process flow diagram for the project is provided in Figure 12.

The same contractor that constructed the plant is also responsible for the daily operation and maintenance work over a 20-year contract period. It is intended that the blending ratio will be increased to 25% when the water reclamation plant is operating at full capacity.

Further developments in South Africa

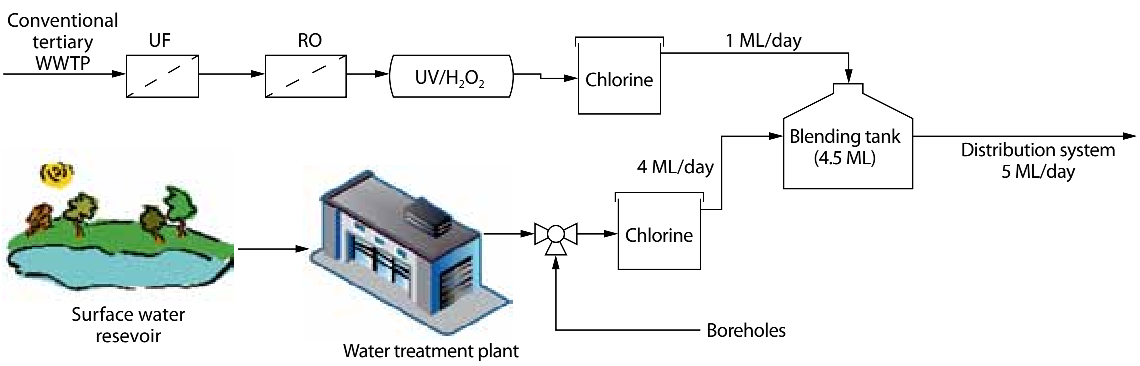
The eThekwini Municipality in South Africa is a metropolitan municipality that includes the city of Durban and surrounding towns. Durban is South Africa's third-largest city and one of Africa's primary commercial hubs, with a rapidly growing population.

In recent years, it has been recognised that the eThekwini Municipality was rapidly approaching a critical water shortage. In 2008, the Municipality began to formally explore water resource alternatives. They considered dams, desalination, water reuse, rainwater harvesting, and a host of other possibilities. Some were considered to be too expensive, others would take too long to implement, and a few were not technically feasible. The preferred alternative was determined to be a DPR project (Golder Associates Africa, 2012).

It was proposed that treated effluent from two wastewater treatment plants (the Northern and KwaMashu WWTPs) would be reclaimed and treated to potable standards. The final preferred treatment train incorporates UF, RO and UV/H_2O_2 advanced oxidation. The highly treated reclaimed water would then be introduced into the existing potable water main of the city's Northern Aqueduct at two separate locations. This specific reuse alternative was reported to have been selected because it was the most cost effective and comprised the most socially equitable combination of the options that were considered. The implementation of this scheme was intended to ensure that the water supply in eThekwini would be secure for a period of seven years, allowing for the phased implementation of desalination schemes and various dams, and/or further DPR schemes.

This proposed development would deliver an additional 116 ML/day of drinking water to the municipality,

Figure 12 Process flow diagram of the Beaufort West DPR Project.



comprising approximately 30% of the total water delivered to affected consumers. 52 ML/day of reclaimed water from the Northern Water Treatment Facilities would comprise approximately 28% of the total volume of water in the distribution infrastructure from the point of introduction. 65 ML/day of reclaimed water from KwaMashu Water Treatment Facilities, plus the 8 ML/day of reuse water remaining in the distribution network from Northern Water Treatment Facilities, would comprise approximately 33% of the total volume of water in the distribution infrastructure from the point of introduction.

The proposed process design allows for three engineered reservoirs each holding 12 hours worth of production. The operational principle is that one reservoir is filled and one reservoir is being tested, while water from the other is being pumped into the distribution system. Once a reservoir is filled a sample is taken and analysed for water quality indicators and free residual chlorine. Additional samples can be taken at the same time and sent to a laboratory for analysis of a more extensive list of parameters.

A 'Basic Assessment Report' for this proposal was prepared for the municipality in 2012 (Golder Associates Africa, 2012). This report included the outcomes of a community consultation exercise and revealed a low level of community support for the proposal. The release of this report was quickly followed by a series of negative media reports during October 2012. As a consequence, the project has since stalled with the elected representatives apparently unwilling to pursue it. Seawater desalination is an alternative water supply option now being actively pursued for eThekwini.

Umgeni Water is the second largest water utility in South Africa and supplies potable water to the eThekwini Municipality. Among the assets of Umgeni Water is the Darvill WWTP (near Sobantu). At present, treated effluent from Darvill WWTP is released into the Msunduzi River, which flows into the Mgeni River and on to the large Inanda Dam. Water from Inanda Dam is treated and purified at Durban Heights or Wiggins Waterworks and pumped to the eThekwini municipal area, including Durban.

Umgeni Water is currently investigating the option of treating effluent from Darvill WWTP to potable standards for DPR. The proposal is to return the treated water back into the distribution system, closer to the source (near Camperdown) rather than allowing it to flow down to Inanda Dam. It is proposed that this reclaimed water could be used to augment the supply to the Western Aqueduct, which carries treated surface water from further west (Midmar Dam). This will then be used to serve the high growth areas along the western corridor of the eThekwini Municipality. The advantage of this is that water is made available higher up in the system and can therefore be supplied using gravity. The alternative is reliant on pumping from Durban Heights WTP to serve these more elevated demand centres.

A number of studies have been undertaken to support the Darvill proposal. These include infrastructure and environmental pre-feasibility studies as well as treatment technology investigations. Preliminary designs and pipeline routes have also been completed. The preliminary process flow for the proposed Darvill Reclamation Plant includes biological treatment by a membrane bioreactor (MBR), ozonation, biological activated carbon, nanofiltration, UV disinfection and chlorination (Umengi Water, 2012).

Umgeni Water, with the approval and sponsorship of the Water Research Commission, is now undertaking a water reclamation pilot plant investigation. The first stage in these investigations involves the installation of the MBR pilot plants. The prime objective is to confirm a satisfactory water treatment process train. The secondary objectives are to assess the operability, stability, economics and risks of such a process (Metcalf *et al.*, 2013). The full feasibility study is expected to be completed in 2014.

Hermanus is a small holiday town on the Western Cape of South Africa (south of Cape Town). Extremely dry conditions in recent years have resulted in town water sources coming under considerable stress. It is currently proposed to develop a DPR project as one of several options to augment the town's water supply. The Hermanus WWTP is to be upgraded and selected advanced treatment processes applied to the effluent. This is intended to provide 2.5 ML/day of potable water, which will be pumped via a new pump station and pipeline into the existing outlet of the Preekstoel Water Treatment Works to supplement the drinking water supply to Hermanus. According to reports published in 2012, a local engineering firm has finalised a design and is proposed to project manage the construction of the scheme.

Key international reports and documentation of DPR

During the past 15 years, a number of important reports and documents have addressed issues relating to the viability or desirability of DPR as a component of water resource management. The most influential of these documents have come from the US, including reports from the National Research Council (NRC), the US Environment Protection Agency (EPA), and water research agencies. A summary of these documents is provided in the following sections, showing the gradual change in attitude that has occurred throughout this period.

Issues in Potable Reuse: The Viability of Augmenting Drinking Water Supplies with Reclaimed Water (NRC, 1998)

The US National Research Council published its first report on potable water reuse in 1998 (NRC, 1998). At that time, the focus was almost exclusively on IPR and only brief mention was made of DPR.

> *Direct potable water reuse is the immediate addition of reclaimed wastewater to the water distribution system. This practice has not been adopted by, or approved for, any water system in the United States.*
>
> *With planned or unplanned indirect potable reuse, the storage provided between treatment and consumption allows time for mixing, dilution, and natural physical, chemical and biological processes to purify the water. In contrast, with direct potable reuse, the water is reused with no intervening environmental buffer.*

The report included the Denver DPR Demonstration Project among a series of case studies demonstrating the viability of potable water reuse in general. However, no further serious analysis of the specific issues that distinguish DPR from IPR were provided. Nonetheless, the report provided the following, somewhat damning, assessment of DPR in the Executive Summary:

> *When considering potable reuse as an option for public water supplies, a critical distinction must be made between "direct" and "indirect" reuse. Direct potable reuse refers to the introduction of treated wastewater (after extensive processing beyond usual wastewater treatment) directly into a water distribution system without intervening storage. Direct use of reclaimed wastewater for human consumption, without the added protection provided by storage in the environment, is not currently a viable option for public water supplies.*

These three, apparently unsupported, sentences appear to have set the tone for DPR for at least the following decade.

US Environment Protection Agency: Guidelines for Water Reuse (2004)

This version of the US EPA Guidelines for Water Reuse (US EPA 2004) is now obsolete as it has been superseded by an update to the document in 2012, as described later in this chapter. Nonetheless, it is insightful to acknowledge the attitude towards the concept of DPR at the time this document was published and to compare that to the more recent documents that follow. This document states that the implementation of “direct, pipe-to-pipe, potable reuse is not likely to be adopted in the foreseeable future in the U.S. for several reasons”:

• Many attitude (opinion) surveys show that the public will accept and endorse many types of nonpotable reuse while being reluctant to accept potable reuse. In general, public reluctance to support reuse increases as the degree of human contact with reclaimed water increases. Further, public issues have been raised relevant to potential health impacts which may be present in reclaimed water.

• Indirect potable reuse is more acceptable to the public than direct potable reuse, because the water is perceived to be "laundered" as it moves through a river, lake, or aquifer (i.e. the Montebello Forebay and El Paso projects). Indirect reuse, by virtue of the residence time in the watercourse, reservoir or aquifer, often provides additional treatment. Indirect reuse offers an opportunity for monitoring the quality and taking appropriate measures before the water is abstracted for distribution. In some instances, however, water quality may actually be degraded as it passes through the environment.

• Direct potable reuse will seldom be necessary. Only a small portion of the water used in a community needs to be of potable quality. While high quality sources will often be inadequate to serve all urban needs in the future, the use of reclaimed water to replace potable quality water for nonpotable purposes will release more high quality potable water for future use.

Water Reuse: Issues, Technologies, and Applications (Metcalf & Eddy. Inc. & AECOM, 2007)

This substantial textbook covers a broad range of issues in potable and non-potable water reuse. The preface for the book indicates that it is intended to provide "specialised instruction of engineering and science students in their undergraduate and graduate levels, as well as practicing engineers and scientists, and a technical reference for project managers and government officials". Chapter 24 of the textbook addresses "Direct Potable Reuse of Reclaimed Water". This chapter provides a number of insightful observations:

Direct potable reuse projects are implemented usually as a result of extreme circumstances, where other potable water alternatives have prohibitive costs or are not available. Depending on particular conditions, direct potable reuse projects may be temporary, as in the event of a severe drought, or long term, for example where a sufficient local water supply does not exist. In any case, several issues are associated with the practice of direct potable reuse, including public perceptions, health risk concerns, technological capabilities, and cost considerations.

Most of the chapter on DPR is then based on three key case studies: an emergency DPR application in Chanute, Kansas (USA) during 1956-57; DPR in Windhoek (Namibia); and the DPR demonstration project in Denver, Colorado (USA). The latter two projects are also described in detail earlier in this chapter. The following concluding observations are then provided:

At present, there is no imperative for the use of reclaimed water for direct potable reuse in the United States: 'Direct use of reclaimed water for human consumption, without the added protection provided by the environment, is not currently a viable option for public water supplies' (NRC, 1998). Nonetheless, direct potable reuse could be a cost-effective form of water reuse in the long-term. While treatment requirements are clearly greater and public acceptance could be a major obstacle, direct potable reuse would have an advantage of avoiding the unnecessary costs of duplicate water distribution and storage systems. Further, direct potable reuse has the potential to readily utilize all the reclaimed water that could be generated and avoid altogether the need to discharge excess flow to the environment. The pressure to consider reclaimed water as a source of potable supply must increase in the future as it seems inevitable that, in time, potable reuse in some form will occur (Hamlyn-Harris, 2001; Law, 2003).

National Water Research Institute White Paper: Regulatory Aspects of Direct Potable Reuse in California (Crook, 2010)

The US National Water Research Institute published 'Regulatory Aspects of Direct Potable Reuse in California', prepared by Environmental Engineering Consultant James Crook (Crook, 2010). It reported that the use of recycled water for non-potable applications "has played an integral role in helping to meet the state's water demands since the early 1900s, and planned indirect potable reuse (IPR) by groundwater recharge of potable aquifers has been practiced in the state since 1962". The current interest in DPR is summarised as follows:

> *Direct potable reuse would provide greater flexibility than IPR to augment some potable water supplies, and there is a growing interest among water utilities, water-related associations, and environmental advocacy groups in California to pursue an assessment of research needs, regulatory requirements, public acceptance, and other factors that need to be addressed for direct potable reuse to be considered in the future.*

The stated purpose of the white paper was to identify issues that would need to be addressed by regulatory agencies and utilities in California interested in pursuing DPR as a viable option in the future. At the time of publication of the white paper, no regulations or criteria had been developed or proposed for DPR in California.

The white paper reported that DPR may be a reasonable option to consider for future projects. This was based on recent significant advances in treatment technology and monitoring methodology, favourable health effects data from IPR projects and DPR demonstration facilities, and water quality and treatment performance data generated at operational IPR projects. However, a number of key regulatory issues that would need to be resolved for DPR be considered were identified. These included:

- **Definition of direct potable reuse** – there needs to be a distinction between what constitutes direct potable reuse versus indirect potable reuse.
- **Environmental buffer** – an environmental buffer is one of the multiple barriers required for IPR projects. Direct potable reuse projects would have no environmental buffer. Means to compensate for the loss of an environmental barrier will likely be required.
- **Multiple barriers** – the number, type and reliability of treatment processes necessary to ensure that constituents of concern are reduced to acceptable levels in the product water would need to be determined.
- **Dilution** – it is not known if dilution would be required as an added safety factor.
- **Monitoring** – increased monitoring of treatment process efficiency and product water would likely be required for direct potable reuse, as well as monitoring techniques that provide feedback in real time or at least very rapidly. Real-time online monitoring is desirable but, with the exception of monitoring for surrogates such as total organic carbon (TOC) and electrical conductivity, may not be achievable with existing technology.
- **Assessment of health risks** – it is not clear what type and level of public health risk assessment would be required for direct potable reuse.
- **Independent Advisory Panels** – it is not known if California Department of Public Health would require scientific peer review of direct potable reuse projects by independent advisory panels.
- **Applicability of existing California Department of Public Health regulations** – an evaluation needs to be made of how existing drinking water statutes, regulations, policies, and permitting processes would apply to direct potable reuse projects.
- **Regulatory responsibility** – the California Department of Public Health (CDPH), State Water Resources Control Board (SWRCB), and Regional Water Quality Control Boards (RWQCBs) may need to consider clarification of the point at which the water makes the transition from Water Code to Health and Safety Code authority.
- **Communication management** – a communication system for the timely sharing of information

must be developed to enable all operating and regulatory agencies involved in direct potable reuse to work together to avoid the distribution of unsafe drinking water.

The white paper provides a summary of health effects studies that have been reported from potable water reuse projects (mainly IPR but some DPR) during the past 30 years. It also provides a discussion on treatment technology, constituents of concern, and monitoring needs.

It is stated that there are suitable advanced water treatment processes available that can reliably reduce these contaminants to "extremely low or immeasurable levels" in recycled water. However, it is also acknowledged that assurance that the product water is consistently "safe" for consumption "is another matter that depends to a large degree on monitoring and its attendant capabilities".

The further development of rapid online monitoring techniques for microbial and chemical contaminants (and/or indicator organisms/chemicals) is identified as "desirable" for this purpose. Furthermore, it is stated that that "it would be advantageous, and perhaps required" to have real-time online monitoring such that microbial and chemical conditions of product water could be determined almost instantaneously. In addition to monitoring, there "needs to be a means for immediate response to prevent the release of product water into a drinking water supply" in the event that it is determined to be of unacceptable quality. On the other hand, it is suggested that real-time monitoring of the product water may possibly be replaced with ongoing treatment barrier performance monitoring.

Much of the remainder of the report deals with issues specific to the potential regulation of DPR in the State of California.

Public and Political Acceptance of Direct Potable Reuse (Nellor & Millan, 2010).

This white paper was prepared by two private consultancy firms for WateReuse California. It addresses challenges related to public perception and acceptance of DPR in California, and identifies potential research areas and communication tools that will be necessary for DPR to gain wide public acceptance. The authors report that DPR projects are expected to face the same challenges faced by IPR projects. However, in order to move forward, at least four challenges should be addressed prior to seeking public support for direct potable reuse:

- The water reuse community must itself support direct potable reuse. At the present time, support within the reuse community is not universal, which will confound efforts to seek public support.
- The water reuse community should develop a standard public involvement program for potable reuse that builds on lessons learned from indirect potable reuse projects, research regarding CEC [constituents of emerging concern] risk communications, and current efforts to invest in simple, accurate, and easy to understand communications about water, including terminology and messages.
- The water reuse community needs to develop public outreach/participation tools to provide a complete picture of the water cycle, including the ubiquitous presence of CECs and their relative risk. This work would involve agreement among the water reuse community about recycled water as "new" versus "regenerated", incorporating the consensus into a framework of how water reuse fits into the water cycle, and to effectively communicate known and perceived risks.
- California will need to develop regulations for direct potable reuse before projects can move forward and be embraced by the public. Even if technology can be proven safe, technology in absence of controls can catalyze mistrust and fear.

Suggestions for research needed to advance direct potable reuse were provide in the white paper and included the following potential topic areas:

- Updated public opinion surveys to evaluate if changes in acceptance of recycled water for drinking and what measures would be effective in building confidence.

- Social research to better understand public perceptions of direct potable water reuse and the psychological factors governing decision-making particularly with regard to accepting or rejecting using recycled water for direct potable reuse.
- Develop key messages about the safety of using recycled water for direct potable reuse in the face of uncertainty.
- Develop and test outreach materials for the public and media for direct potable reuse.

State of California Senate Bill 918 (2010) and the California Water Code

The Governor of the State of California (USA) signed into law Senate Bill 918 in September 2010. This was an Act to provide amendments and additions to the California Water Code, specifically relating to water recycling. Senate Bill 918 requires the California Department of Public Health (CDPH) to investigate the feasibility of developing regulatory criteria for DPR and to provide a final report on that investigation to the Legislature by the end of 2016.

The relevant amendments to the California Water Code now appear in Sections 13560 to 13566 of the Code. They state that: "The use of recycled water for indirect potable reuse is critical to achieving the state board's goals for increased use of recycled water in the state. If direct potable reuse can be demonstrated to be safe and feasible, implementing direct potable reuse would further aid in achieving the state board's recycling goals". The Code acknowledges that there has been much scientific research on public health issues associated with IPR through groundwater recharge, but indicates that there are a number of significant unanswered questions regarding IPR through surface water augmentation and DPR. Nonetheless, "achievement of the state's goals depends on the timely development of uniform statewide recycling criteria for indirect and direct potable water reuse".

Consequently, the CDPH will be required to adopt uniform criteria for IPR through groundwater recharge by the end of 2013, and to do the same for IPR through surface water augmentation by the end of 2016. Concomitantly, the CDPH must provide a report (to be made publicly available) on the feasibility of developing uniform criteria for DPR by the end of 2016. In conducting this investigation, the CDPH must examine all of the following:

> *(1) The availability and reliability of recycled water treatment technologies necessary to ensure the protection of public health.*
> *(2) Multiple barriers and sequential treatment processes that may be appropriate at wastewater and water treatment facilities.*
> *(3) Available information on health effects.*
> *(4) Mechanisms that should be employed to protect public health if problems are found in recycled water that is being served to the public as a potable water supply, including, but not limited to, the failure of treatment systems at the recycled water treatment facility.*
> *(5) Monitoring needed to ensure protection of public health, including, but not limited to, the identification of appropriate indicator and surrogate constituents.*
> *(6) Any other scientific or technical issues that may be necessary, including, but not limited to, the need for additional research.*

In addition, the CDPH must convene and administer an expert panel for the purposes of advising the department on public health issues and scientific and technical matters regarding the activities described above. In performing its investigation of the feasibility of developing the uniform water recycling criteria for direct potable reuse, the department must consider a number of sources of information including recommendations from the expert panel, as well as regulations and guidelines from jurisdictions in other states, the federal government, or other countries.

Direct Potable Reuse: The Path Forward (Tchobanoglous *et al.*, 2011)

The report 'Direct Potable Reuse: A Path Forward' (Tchobanoglous *et al.*, 2011) was commissioned and published by the (US) WateReuse Research Foundation and Water Reuse California. It was developed (at least partially) in response to Californian Senate Bill 918, as described above, with the stated purpose being "to provide a general overview of current knowledge related to DPR and to identify the information that must develop through targeted studies to inform the public, public and private water agencies, and regulatory agencies regarding the feasibility of implementing DPR as a viable water supply management option". The scope of the report is to identify information and types of research studies that are necessary to provide a starting rationale for the discussion of the feasibility of DPR, including engineering, economic, regulatory, and public acceptance considerations.

The report provides a good summary of key issues, including a useful discussion of engineered storage buffers and the role that they may play in future DPR systems. A summary of technical issues in the implementation of DPR is presented in Table 2.

This report also provided a useful analysis and summary table of public acceptance issues in the implementation of DPR. Finally, the report provides a list of proposed research projects to be undertaken in order to address some of the key questions requiring improved knowledge to aid in the wider or improved implementation of DPR. For each project, summaries of the rationale, objectives, and proposed benefits are provided in the report. Eight specific projects were proposed, with the titles as listed below:

1. Design considerations for sizing engineered storage buffers
2. Impacts of treatment train process operation modifications to enhance the performance and reliability of secondary, tertiary, and advanced treatment systems
3. Evaluation of blending requirements for purified water
4. Enhanced monitoring techniques and methods for direct potable reuse
5. Equivalency of advanced wastewater treatment trains and processes for direct potable reuse
6. Develop standard terminology, messaging, and communication materials for planning and implementation of DPR
7. California direct potable reuse summit (addressing acceptance of DPR among the water community)
8. Effect of prior knowledge on the acceptance of planned potable reuse in California

Water Quality & Treatment: A Handbook on Drinking Water (AWWA)

Among the most important and widely used drinking water quality and treatment handbooks is *Water Quality & Treatment: A Handbook on Drinking Water,* produced by the American Water Works Association. The sixth edition reflects the growing interest in potable water reuse by the inclusion of a new chapter on Water Reuse for Drinking Water Augmentation (Drewes & Khan, 2011). While most of the chapter deals primarily with IPR, brief attention is given specifically to DPR as an option for potable reuse:

> *The determining factor for direct potable reuse is public confidence in, and reliance on employed water treatment processes that always produce safe drinking water. Technological concerns are addressed by multiple barrier systems, providing redundancy and diversity of processes that can remove the wide range of constituents of concern producing a water quality that meets drinking water standards and is safe to drink. In addition, process validation and verification approaches through real-time and frequent monitoring are available today and already embedded in many advanced water treatment plants practicing indirect potable reuse worldwide. What remains challenging is to overcome public and regulator perception to potable reuse. Direct potable reuse, however, offers opportunities to significantly reduce the cost for water collection and water distribution systems that might become more relevant in the near future making direct potable reuse a cost effective application in the long term.*

Table 2 Technical issues in the implementation of direct potable reuse (Tchobanoglous *et al.*, 2011).

Consideration	Comments/questions
Source control	• Identification of constituents that may be difficult to remove (depends on technologies used). • Development of baseline sources and concentrations of selected constituents. • Define the improvements that need to be made to existing source control programs where DPR is to be implemented.
Influent monitoring	• Development of influent monitoring systems, including constituents, parameters, and monitoring recommendations. • Investigate potential benefits of various influent monitoring schemes that may be used for early detection of constituents. • Consideration of how influent monitoring data could be used to adapt treatment operations depending on variable influent characteristics.
Flow equalization	• Determination of the optimum location and type (in- or off-line) in secondary treatment process with respect to enhanced reliability and removal of trace constituents. • Determination of optimum size of flow equalization before advanced treatment. • Quantify the benefits of flow equalization on the performance and reliability of biological and other pre-treatment processes.
Wastewater treatment	• Quantify benefits of optimizing conventional (primary, secondary, and tertiary) processes to improve overall reliability of entire system. • Quantify the benefits of complete nitrification or nitrification and denitrification on the performance of membrane systems used for DPR applications.
Performance monitoring	• Determine monitoring schemes to document reliability of treatment performance for each unit process and validate end of-process water quality.
Analytical/monitoring requirements	• Selection of constituents and parameters that will require monitoring, including analytical methods, detection limits, quality assurance/quality control methods, and frequency. • Determination of how monitoring systems should be designed in relation to process design. • Development of appropriate monitoring systems for use with alternative buffer designs.
Advanced wastewater treatment (water purification)	• Develop baseline data for treatment processes employing reverse osmosis. Orange County Water District can be used as a benchmark. • Development of alternative treatment schemes with and without demineralization that can be used for water purification. • Quantify benefit of second stage (redundant) reverse osmosis.
Engineered storage buffer	• Development of sizing guidelines based principally on existing analytical, detection, and monitoring capabilities to assess technical and economic feasibility of utilizing engineered storage buffer. • Characterize the impact of existing monitoring response times on the safety and economic feasibility of implementing an engineered storage buffer.
Balancing mineral content	• Development of recommendations for balancing water supply mineral content in consideration of site-specific factors, such as magnesium and calcium. • Determination of potential impacts of various water chemistries on infrastructure and public acceptance. • Development of specifications for chemicals used for balancing water quality.
Blending	• Development of guidance on what level of blending, if any, is required based on the quality of the purified water and alternative water sources. • Investigation of the significance of and rationale for blend ratios in terms of engineered buffer, protection of public health, public acceptance, and regulatory acceptance. • Investigation of potential impacts of purified water on drinking water distribution system, e.g. corrosion issues, water quality impacts, etc.
Emergency facilities	• Stand-by power systems in the event of power loss or other emergency. • Availability of all replacement parts and components that would be required in the event of a process breakdown. • Process redundancy so that treatment trains can be taken offline for maintenance. • Facilities for the by-pass or discharge of off-specification water in the event that the water does not meet the established quality requirements.
Pilot testing	• Utilisation of a review panel for advice and recommendations on the design, operation, and monitoring plan for a project's pilot system to ensure that it will be representative of the proposed full-scale system. • Development of monitoring protocol for collection of baseline data for "raw" water input to AWT pilot plant; how much testing and for what duration (e.g. 6 months to 1 year). • Development of pilot study design so that results can be used to assess reliability with proposed source water.

Direct Potable Reuse: Benefits for Public Water Supplies, Agriculture, the Environment, and Energy Conservation (Schroeder *et al.*, 2012)

This White Paper, published by the National Water Research Institute, examined a range of potential advantages of DPR with a focus on Southern California as an example. The four key areas of potential benefits considered were benefits for public water supplies, benefits for agriculture, benefits for the environment and benefits in terms of reduced energy requirements for pumping water.

The benefits for public water supplies are largely identified as the avoidance of various disadvantages associated with alternative solutions to meet urban water supply requirements. For example, inter-basin transfer of water (which is very significant in California) is associated with the loss of water for food production, destruction of source area ecosystems and transmission systems that are subject to damage from earthquakes, floods and other natural and human-made disasters. Seawater desalination is noted for its high energy requirements and comparatively large volumes of brine requiring disposal. It was proposed that, by comparison, "DPR will have relatively modest energy requirements and provide a stable local source of water that is less subject to natural disasters". Furthermore, it was suggested that the application of DPR to create decentralised water resource systems would facilitate the use of reduced pumping and energy consumption.

The benefits to agriculture were based on the reduced need for water to be exported from agricultural areas for urban use. It was argued that there is an increasing need for water for food production in many parts of the world and that DPR may enhance the availability of water for this purpose.

The benefits for the environment were described principally in terms of the elimination or minimisation of water importation to cities through inter-basin transfers, reducing environmental impacts resulting from the construction of dams (reservoirs) and canals.

The benefits in terms of reduced energy requirements for pumping water were also described by comparison with inter-basin transfers of water. In California, such transfers often require large expenditures of energy to pump water over mountain ranges that separate and define the basins.

An analysis provided in this paper indicated that by using a portion of the treated wastewater now being discharged to the Pacific Ocean through the application of DPR could provide a number of specific advantages in Southern California. These included the stabilisation of water supplies for both Southern California and San Joaquin Valley agriculture, significantly decreasing the energy required for transporting water, protecting and enhancing the ecosystems of the Sacramento-San Joaquin Delta, and decreasing the pollution of near-shore waters and beaches in Southern California. The report found that DPR was a technically feasibly method of achieving these outcomes, but that its application on a large scale "will raise significant political issues related to the ownership of water that will need to be resolved". The authors argue that "it is clear that the water and wastewater industry should undertake an initiative to develop a planning process to examine the potential of DPR and impediments to its implementation". Further, they advocate some clear activities for planning for a future which includes DPR in the overall water management program:

> *One of the major steps that should be taken by the water and wastewater industry is to develop closer ties with respect to the management of available water resources. As water distribution system modifications and replacements are planned and implemented, attention should be focused on appropriate locations within an existing system where engineered storage buffers or water purification plants can be located (e.g., near existing water treatment plants or other suitable locations within the service area). Studies should be undertaken to assess what blending ratios would be acceptable with the existing water supply to protect public health, maintain water quality, and control corrosion.*

Water Reuse: Potential for Expanding the Nation's Water Supply Through Reuse of Municipal Wastewater (National Research Council, 2012)

This comprehensive report from the National Research Council is effectively an update of the previous report 'Issues in Potable Reuse' (National Research Council, 1998) described earlier in this chapter. Unlike the earlier report, the current NRC Committee supported the consideration of DPR as a viable means of augmentation of drinking water supplies. When considering the distinction between IPR and DPR, the report offers the following insightful discussion on the purpose and role of an "environmental buffer" for IPR:

> *An environmental buffer is a water body or aquifer, perceived by the public as natural, which serves to sever the connection between the water and its history. The buffer may also (a) decrease the concentration of contaminants through various attenuation processes, (b) provide an opportunity to blend or dilute the reclaimed water, and (c) increase the amount of time between when the reclaimed water is produced and when it is introduced into the water supply. Although the latter three functions of environmental buffers have potentially important implications for public health, performance standards for buffers have never been defined. The committee is unaware of any situation in which the time delay provided by a buffer has been used to respond to an unforeseen upset, and the residence time of reclaimed water in some environmental buffers (e.g., rivers, small lakes, and reservoirs) is short (e.g., hours or days) relative to the time needed to detect and respond to all but the most obvious system failures.*

Although certain potential advantages from the use of environmental buffers are acknowledged, the NRC Committee did not consider their use to be essential for potable reuse projects, from a public health perspective:

> *It was largely the passage of water through a natural system and its role in increasing public acceptance of the subsequent use of the water in potable supplies that led to the perception that environmental buffers were essential to potable water reuse projects. For the community, environmental buffers have been crucial to acceptance because they break the perceived historical connection between the ultimate water source (i.e., sewage) and the reclaimed water supply.*

In fact, the committee reported that uncertainty regarding their performance in improving water quality was an important limitation of many environmental buffers:

> *The role of the environmental buffer in providing public health protection under the conditions encountered in planned potable reuse systems has not always been well documented. This is particularly important because each environmental buffer will have different attributes that affect the removal of contaminants, the amount of dilution, or the residence time. For example, greater removal of contaminants by photochemical processes will occur in shallow, clear streams than in deep lakes or turbid rivers (Fono* et al.*, 2006). As a result, it would be inappropriate to assume that contaminant attenuation by photochemical processes occurs at the same rates in these two types of systems. Without good data on site-specific characteristics, there will be considerable uncertainty about the ability of environmental buffers to remove contaminants.*

Consequently, the committee argued that "the classification of potable reuse projects as indirect (i.e., includes an environmental buffer) and direct (i.e., does not include an environmental buffer) is not productive from a technical perspective because the terms are not linked to product water quality". Hence throughout much of this report the term 'potable reuse' is applied without either preceding adjective:

Because of the limited and variable data on the performance of environmental buffers, the committee has chosen in this report to emphasize the key processes and attributes necessary for potable reuse, rather than specific design elements implied by the terms direct or indirect potable reuse. Thus, these terms are mainly used in this report in the context of historical or planned reuse projects, in recognition of the widespread practice of classifying potable reuse projects as direct or indirect, but these distinctions are deemphasized in the remainder of the report.

This report also provides a useful discussion of some of the reasons that US utilities have become particularly interested in DPR in recent years. These include "water rights, lack of suitable buffers near the locations where reclaimed water is produced, potential for contamination of the reclaimed water when it is released into the environmental buffer, and costs associated with maintenance, operation, and monitoring of environmental buffers". Amongst the examples provided is that of Big Spring, Texas, as described earlier in this chapter. It is stated that "in addition to decreasing the water district's reliance on the Colorado River, the reuse of water avoids the need to pump water up to the reservoir from water sources lower in the watershed. As a result, after including energy used by the advanced treatment plant, energy consumption for the reclamation project is approximately equal to that of other available water sources". Further insights are provided by the following comments regarding water rights obstacles encountered for an IPR project in Georgia:

For example, recent controversies about water rights in Lake Lanier, Georgia, could jeopardize the Gwinett County Water Authority's rights to the reclaimed water that it currently discharges to the lake. As a result, it is considering the possibility of piping the reclaimed water directly to a blending pond that is not connected to the reservoir, thereby allowing them to maintain ownership of the water. Because the blending pond would be a manmade structure that does not receive water from other sources, this potable reuse project would not include an environmental buffer.

US Environment Protection Agency: Guidelines for Water Reuse (2012).

This most recent revision of the *US EPA Guidelines for Water Reuse* (2012) reveals a sharp change in attitude regarding the future implementation of DPR in the US relative to the previous revision in 2004, as described earlier in this chapter. This change in thinking appears to be clearly influenced by the assessments provided in a number of other more recent documents, including those described previously in this chapter.

The Guidelines state that DPR may now "be a reasonable option based on significant advances in treatment technology and monitoring methodology in the past decade and health effects data from IPR projects and DPR demonstration facilities". With specific reference to data collected from a number of US-based IPR projects, the Guidelines conclude that the advanced wastewater treatment processes in place in these projects can meet the required purification level.

The case for including DPR among the various water supply options that may be considered in a particular circumstance is based largely on the potentially advantageous environmental, financial and reliability attributes of DPR compared to some alternatives:

In many parts of the world, DPR may be the most economical and reliable method of meeting future water supply needs. While DPR is still an emerging practice, it should be evaluated in water management planning, particularly for alternative solutions to meet urban water supply requirements that are energy intensive and ecologically unfavorable. This is consistent with the established engineering practice of selecting the highest quality source water available for *drinking water production. Specific examples of energy-intensive or ecologically-challenging projects include interbasin water transfer systems, which can limit availability of local water sources for food production, and source area ecosystems, which are often impacted by reduced stream flow and downstream water rights holders who could exercise legal recourse to regain lost water. In some circumstances, in addition to the high energy cost related to long-distance transmission of water, long transmission systems could be subject to damage from earthquakes, floods, and other natural and human-made disasters. Desalination is another practice for which DPR could serve as an alternative, because energy requirements are comparatively large, and brine disposal is a serious environmental issue. By comparison, DPR using similar technology will have relatively modest energy requirements and provide a stable local source of water.*

Chapter 5 Identification of key issues – qualitative survey of Australian stakeholders

A qualitative survey was undertaken for the purpose of identifying the range of potentially significant issues that would need to be addressed in order to make a comprehensive assessment of the benefits and risks of implementing a DPR project in Australia.

The survey was constructed using an online survey tool (SurveyMonkey) and the online address was distributed to survey participants by email. Distribution was targeted to Australian individuals and organisations with known interests in wastewater management, drinking water management and/or water reuse. In all, 80 survey responses were received from a variety of industry bodies, academic organisations, state government departments and agencies, health regulators, drinking water providers/managers, local government associations, local governments, Commonwealth Government departments and agencies, interested individuals, and private companies.

Efforts were made to acquire the views of a diverse range of stakeholders. For example, all members of the ATSE Water Forum were invited to participate, regardless of their particular experience or past interest in water recycling. Furthermore, direct invitations were made to four community members considered to have been highly vocal opponents to previous potable water recycling proposals in Australia. Unfortunately, only one agreed to participate in the survey.

Of the 80 responses received, 91% indicated that that the information provided represented their personal views. Only 15% indicated that the information presented the view of their organisation or department.

As a consequence of the broad range of participants, an equally broad diversity of opinion was captured within the survey comments. Indeed, some of the comments received clearly contradict others. ATSE does not endorse, nor necessarily agree with, any of the comments received. In fact, there are many for which ATSE believe there exists contradictory evidence. No such commentary is provided in the following sections, but relevant available evidence is presented within the other chapters of this report.

A comprehensive summary of the responses received for this survey is included as Appendix A to this report. It is available online at www.atse.org.au/water-reports. A more concise summary is provided in this chapter.

Background information provided to the survey participants

The following background information was provided to the survey participants and as an introductory section to the online survey.

> *INTRODUCTION: WHAT IS MEANT BY 'DIRECT POTABLE WATER REUSE'?*
> *During the past decade, there has been much discussion in Australia regarding the development of planned 'indirect potable reuse' (IPR) schemes. Prominent examples of IPR include the unsuccessful proposal for the City of Toowoomba (2006), the construction of the Western Corridor Recycled Water Project in South-East Queensland (2007-2009) and the successful Groundwater Recharge Trial in Perth (2010-2013). The concepts underpinning all of these IPR projects include:*
> 1. *Water is sourced from municipal wastewater treatment plants (sewage treatment plants).*
> 2. *The water is then treated to a very high level using advanced water treatment technologies.*
> 3. *The water is then returned to an 'environmental buffer' such as a river, lake, reservoir or groundwater aquifer where it mixes with waters from other sources.*
> 4. *The mixed water is re-extracted from the 'environmental buffer' for conventional drinking water treatment and distribution to customers as a component of the municipal drinking water supply.*
>
> *The concept being examined in the current survey is direct potable reuse (DPR).This DPR differs from the above description of IPR by the exclusion of the 'environmental buffer' (step 3). That is, the highly treated water is not returned to a river, lake, reservoir or groundwater aquifer, but is instead treated to a level that is appropriate for direct distribution to customers as a component of the municipal drinking water supply. As such, the water may be delivered direct to the distribution system (or alternatively, blended with other sources of water and further treated via an existing water treatment plant).*

An illustration was then provided to summarise the concept of DPR and its distinction from IPR. This illustration is included in Appendix A.

Instructions given to the survey participants

The instructions given to the survey participants were as follows:

> *The following questions have been designed to solicit and organise input to this study by key stakeholders. They relate to specific areas of interest to the project. However, you are encouraged to provide whatever information that you feel is appropriate, even if it does not appear to be directly solicited by any of these questions. You are encouraged to elaborate as much as possible on all answers.*

Participant background knowledge

Of the 80 survey respondents, 79 (99%) indicated that they were familiar with the concept of IPR prior to reading the above survey introduction. Furthermore, 73 (91%) of the participants indicated that they were familiar with the concept of DPR.

However, it should be noted that the actual degree of familiarity and direct experience with such schemes is expected to vary significantly among the participants. Some of the comments received appear to indicate that some participants did not necessarily have a clear understanding of what is implied by DPR. For example, the following comments were received in response to the question regarding whether the participants could "identify any perceivable benefits of DPR (compared to IPR)":

I think DPR can be beneficial in some industrial applications. A good deal of recycled water in Queensland is supplied to power generation plants, which do not need IPR. Agricultural use may also benefit from DPR. Generally I think IPR can be used in many settings, and would think IPR is more of a community drinking water solution.

Possibly for industrial use but don't see it being acceptable for a long time for domestic use.

Survey participant responses to key issues are presented in the following sections.

Role(s) of the environmental buffer in IPR

QUESTION:
What do you consider to be the role(s) of the 'environmental buffer' in IPR? In your opinion, how necessary is the 'environmental buffer' in performing such role(s)?

A variety of roles were identified for the 'environmental buffers' of IPR. These included both performance-based roles, leading to improved water quality and/or water safety, as well as a number of public perception-related roles.

Negligible purpose

A significant number (approximately 20%) of the survey respondents indicated that they considered the environmental buffer of IPR schemes to serve negligible purpose. In most cases, this was based on the belief that engineered water treatment processes could provide the necessary water quality and additional improvement by environmental buffers was either not significant or not required. In one case, belief that environmental buffers served negligible purpose appeared to be based on the assumption that health authorities would be unlikely to permit unsafe water to be discharged upstream of drinking-water off-takes.

There is a sense that environmental buffers are somewhat of a relic of earlier developments in water recycling, having once played an important role, but that role now diminished with more modern schemes and practices. A common observation was that, as opposed to providing water quality improvements, environmental buffers may, in fact, have a detrimental impact on water quality. Furthermore, it was suggested that the inclusion of an environmental buffer confounds the public communication message that highly treated recycled water is safe to drink.

To provide a 'perception' of increased water quality or safety/public confidence

A commonly identified purpose for the inclusion of environmental buffers in potable water recycling projects was to enhance public confidence in the system or to provide a perception of increased water quality or safety. Note that this perception of increased water quality or safety is assumed to be distinct from the provision of actual increased water quality or safety, which is addressed in a subsequent section.

To provide a perception of a disconnection between treated effluent and raw drinking water, to reduce the 'yuck factor'

Many respondents (approximately 25%) indicated that the environmental buffer provides a perception of a 'disconnection' between treated effluent and raw drinking water. With such a disconnection, the water is assumed to lose its 'identity' as tarnished 'sewer water' and start anew as 'environmental water' to be treated to produce drinking water. This 'loss of identity' is clearly distinct to the perception of actual additional water treatment or improved safety, as described previously. Numerous responses referred to the well-known 'yuck factor' that has commonly been associated with potable water recycling. This is fundamentally based on recognition of the water's history as sewage. Accordingly, it was assumed that such references to environmental buffers being used to overcome or reduce the 'yuck factor' were indeed references to its role in providing this perceived disconnection between sewage and drinking water.

To demonstrate that the project is following established international practice for potable reuse

One respondent provided the observation that the use of environmental buffers for potable water reuse is a much more established practice compared to DPR. Accordingly, continuing to use them provides a reassuring message to the community that the industry is following established international practice as opposed to trying out something new.

To make potable reuse more socially acceptable (without a clearly articulated explanation)

Further responses indicated that an important role of the environmental buffer was to increase public acceptance generally, but did not provide sufficient additional information to enable an interpretation of how this was achieved. In other words, it was not clear which of the above three categories (if any) many of the additional responses belonged to.

To provide an additional treatment barrier for pathogenic and/or trace chemical substances

Many respondents (approximately 60%) indicated that the environmental buffer had a legitimate, or important, role in providing a further treatment process for recycled water – beyond simply the public perception of this role. Among the various comments, this role was described as being potentially effective for nutrients, trace chemical contaminants and pathogenic microorganisms.

Many of these comments suggest that the treatment role of the environmental buffer is for 'everyday' routine improvement to water quality. However, a few of the respondents suggest that the treatment role of the environmental buffer is predominantly as an 'emergency back-up' to be relied upon only when other processes fail.

To provide dilution of contaminants in recycled water

In addition to water treatment by actual chemical removal or pathogen inactivation, some respondents identified dilution of recycled water constituents as a function of environmental buffers.

To stabilise/equilibrate highly purified reverse osmosis permeates

It is known that water directly produced by reverse osmosis membrane filtration (i.e. 'reverse osmosis permeates') can be exceptionally low in concentration of dissolved minerals such as calcium and magnesium. Such low mineral content can render water highly 'aggressive', which means that the water has a high potential to corrode and degrade many water infrastructure materials including concrete and metallic pipes. Low mineral content is also known to detrimentally affect drinking water taste. Two survey respondents indicated that the environmental buffer may play a role in 'remineralising' water subsequent to reverse osmosis treatment.

To provide 'time to respond' to treatment malfunctions or unacceptable water quality

Among the most commonly identified roles of environmental buffers was the provision of 'time to respond' to any incidents of unacceptable water quality from the advanced water treatment plant. It was suggested that if a water quality 'incident' occurs, or water quality objectives are not met, the buffer provides some period of delay before the water is delivered to consumers. The implication is that this period of delay then provides the necessary time to identify the incident and respond by the implementation of some additional means of water quality management.

Buffering the production and use of recycled water/storage

As the term implies, an environmental 'buffer' may provide an important 'buffering' function. That is, the storage capacity of the environmental buffer facilitates balancing variable mismatches between the production of recycled water and its demand. This buffering may manage these water supply/demand variations on an hourly, daily, seasonal or even annual basis. A number of respondents identified buffering as an important role.

Providing environmental outcomes/protecting water resources

Two respondents indicated that an environmental buffer could be used to benefit the environmental system itself or provide for the enhanced protection of natural water resources. However, other respondents expressed concern for potential negative impacts on natural systems used as environmental buffers.

Perceivable benefits of DPR

QUESTION:
Can you identify any perceivable benefits of DPR (compared to IPR) that may apply in some (hypothetical) future circumstances? In other words, why might DPR ever be an idea worth considering above IPR?

A range of potential benefits to DPR was identified. These include potential cost savings, some of which were related to reduced energy requirements for transporting water. Improved flexibility, such as the ability to practise potable reuse in the absence of a suitable environmental buffer, was also proposed. Elimination of an environmental buffer was seen to have potential benefits derived from the maintenance of high quality water, produced by advanced treatment processes, without contamination by environmental sources. A number of respondents were unable to identify any particular benefits for DPR.

Improved economics/ cost effectiveness

Respondents commonly presumed that DPR was less costly than IPR. Some respondents referred to savings in capital infrastructure costs while others highlighted savings in operational costs, such as reduced energy requirements for water transport, reduced water treatment costs, and reduced land management costs. Many respondents indicated a relatively high degree of uncertainty about these cost savings and some pointed out that they would be highly case-specific.

Two respondents noted that DPR could help defer major upgrades of existing water infrastructure. One respondent noted that DPR could avoid the potential costs of IPR associated with integrated land, vegetation, and water management. However, another respondent argued that it was unrealistic to expect substantial capital and operational cost savings from DPR over IPR in most existing urban areas – the cost and complexity of establishing distributed nodes within existing drinking water systems to receive the output of treatment plants could erode the potential cost savings of locating these nodes closer to end-consumers.

Reduced energy requirements

As discussed above, reduced energy requirements were commonly identified as an important source of presumed cost savings from DPR. However a number of responses appeared to imply that reduced energy requirements had additional implications beyond reduced costs. A number of respondents separately mentioned both reduced energy requirements and reduced costs. Others mentioned reduced energy requirements without any mention of costs. A small number specifically stated that reduced energy implied "a more sustainable solution", "better environmentally" or "environmental benefits". Only a single comment explicitly referred to a "lower carbon footprint", but it is assumed that this is implied in most of these responses.

Improved flexibility of water supply

Two respondents suggested that the avoided need to include the services of an environmental buffer in a potable water reuse scheme would improve flexibility in scheme design and/or operation.

Improved water supply security/emergency water supply

A number of respondents indicated that the adoption of DPR as a component of municipal water supply could improve the overall security of supply. The means by which this may be achieved were relatively diverse and included the use of DPR as an emergency or ongoing supply during drought periods. Others suggested that DPR could be more resilient to extreme weather events such as floods when conventional sources might be susceptible to contamination.

Maintenance of high water quality produced by advanced treatment processes/improved water quality control

Many respondents identified a potential advantage of DPR as the maintenance of high water quality produced by an AWTP as the water is transferred either to a subsequent drinking water treatment plant or direct to a distribution system. This is clearly in contrast with many IPR systems where the water may be subject to detrimental impacts to quality while maintained in an environmental buffer. Identified consequences of this 'quality maintenance' included reduced demand on subsequent treatment processes, reduced exposure to environmental risks and potentially higher quality finished water for distribution.

Reduced chemical consumption and/or waste production

A few respondents suggested that maintaining the high quality of water produced by an advanced water treatment plant, and avoiding mixing with lower quality environmental waters, would reduce potable water treatment requirements. Such reductions in treatment requirements would lead to a number of additional benefits including reduced chemical consumption and reduced waste production.

Ability to practise potable reuse in the absence of a readily available suitable environmental buffer

Many respondents pointed out that some areas simply lack suitable environmental buffers that can be readily used in IPR. In such circumstances, DPR could be an option to realise potable reuse.

Minimisation of losses from an environmental buffer/storage

Several respondents identified DPR as being more water efficient than IPR due to the avoidance of potential losses from environmental buffers. Sources of water losses included evaporation from surface water reservoirs and incomplete recovery from recharged aquifers.

Opportunity for decentralisation

A few respondents identified DPR as an opportunity for decentralisation of urban water systems, particularly where centralised supply was costly.

Improved flood mitigation capacity

One respondent noted that a switch to DPR from IPR could free up capacity in environmental buffers for use in flood mitigation.

Avoidance of contamination of environmental buffer/environment with contaminants in recycled water

Several respondents viewed DPR as a solution to the potential problem of contaminating environmental buffers with poorly treated water.

More logical public communication message

Two respondents considered that DPR was easier to explain to the public.

More responsive supply-demand profile

Two respondents considered that DPR could deliver timelier water supply in response to changing demand.

No benefits identified

Several respondents did not see any benefits from DPR, and two respondents did not see any benefits from either DPR or IPR.

Perceivable obstacles to DPR

QUESTION:
Can you identify any perceivable obstacles to DPR (compared to IPR) that may apply in some (hypothetical) future circumstances? In other words, why might DPR be less attractive or more difficult to implement than IPR?

The diversity of opinion about perceivable obstacles to DPR illustrates the complex interaction between the issues involved (e.g. health, safety, cost, and regulation), perceptions, and individual and group responses. A large number of respondents commented on the public's negative perceptions about consuming recycled water and the public's lack of confidence in the safety of treatment technologies and the trustworthiness of operators. Some respondents noted that these sentiments appeared to be shared by some policy makers, water managers, and regulators.

Public acceptance, as distinct to perception

A number of respondents noted that DPR lacked community acceptance and/or wider public acceptance. Explanations for the poor public acceptability of DPR included consumers' clear preference for traditional water supplies and a lack of public confidence in advanced treatment technologies. DPR was also seen as an unproven approach. One respondent saw potable reuse as a forced solution.

Public perception – the 'yuck factor'

As discussed above, several respondents noted the public's disgust – 'yuck' – at the thought of directly consuming treated water. An environmental buffer was seen as an (at least partially) effective way to overcome the public's first impressions of treated water as having come from sewage. This is aligned with earlier comments regarding the role of the environmental buffer in providing a 'disconnect' between wastewater as the source and drinking water as the product.

Public perception – inherent poor water quality or lack of safety

A number of respondents noted a lack of public confidence in the safety of advanced treatment technologies and in the trustworthiness of operators. Although these concerns may also apply to IPR schemes, it was suggested by some that they may be magnified for DPR. This was attributed to the absence of an environmental buffer as an additional treatment barrier as well as an opportunity to mitigate treatment failures (i.e. 'time to respond'), should failures occur.

Several respondents pointed to the need for strategic public awareness campaigns in order to demonstrate the safety and efficacy of DPR. However other respondents noted that the public interpreted adequate safety as being necessarily 'fail-safe'. In particular, human error was a risk that the public was unwilling to tolerate.

One respondent offered an observation as to why, alternatively, DPR might be perceived more favourably by the public in terms of water quality and risk than IPR. The use of an environmental buffer in IPR could give the impression that the treated water was not yet of an adequate standard for consumption.

Public perception regarding non-equal distribution of recycled water

One respondent considered that the relative proportions of recycled water delivered to specific sections of the distribution system could have an impact on public perception. That is, negative perception may be generated if it were the case (or perceived to be the case) that some areas received higher proportions of recycled water, while others received more conventionally sourced water. In this case, more favourable public perception would depend upon recycled water being relatively evenly distributed within a distribution system. This would include even levels of distribution to both high and low socio-economic communities.

Public perception – no further explanation provided

Numerous respondents also identified "public perception" or "community perception" as an obstacle but without further explanation.

Lack of political will

Several respondents saw DPR as a difficult and unpopular issue politically.

Lack of global precedents

One respondent though that local acceptance of DPR depended on DPR's global acceptance. It was noted that the few current global examples of DPR did not provide a large basis for global acceptance.

Lack of regulatory framework and/or regulatory competency or regulatory acceptance

Several respondents suggested that existing regulatory gaps would need to be addressed before DPR was more widely accepted or could be implemented. Some comments noted that local regulators might lack the technical capacity to deal with the necessary approvals for DPR schemes.

Lack of industry competency

One respondent suggested that the water industry might lack the competence to manage the risks of DPR effectively.

Risks of poor water quality

Some respondents indicated a concern that the treatment barriers to be used for a DPR project may not be sufficient to remove all important contaminants to below safe levels for drinking water. Endocrine disrupting chemicals were specifically mentioned, as were issues associated with 'mixture effects' of complex low concentration mixtures of chemicals. Furthermore, treatment process by-products (e.g. disinfection by-products) were mentioned including those that may be particular to some advanced water treatment processes (e.g. ozonation).

Risk of a water quality incident and loss of 'time to react'

A number of respondents suggested that risks associated with water quality incidents may be more significant for DPR schemes than for IPR. Particular modes of water quality incidents identified included accidental contamination, treatment process failure, sabotage, and terrorism. To these respondents, the absence of an environmental buffer implied both a loss of treatment redundancy ('multiple barriers') as well as the loss of 'time to react' to incidents.

Belief that the environmental buffer is necessary

Two respondents felt that the public commonly believed that an environmental buffer was simply necessary for potable reuse. This belief was also attributed to some water industry professionals.

High costs associated with DPR

As discussed above, a number of respondents thought that DPR would result in cost savings. However, a smaller number of respondents thought that DPR would result in higher costs, particularly higher water treatment and monitoring costs.

Need for additional risk management measures compared to IPR

Some respondents reported that DPR would require more sophisticated risk management. Although generally not explicitly stated, it may be assumed that the obstacles identified here are the additional costs associated with increased risk management and/or the possibility that sufficiently sophisticated techniques are not currently available.

Need for real-time monitoring exceeding current capabilities.

Two respondents noted the need for real-time monitoring of DPR and expressed concern about whether this could currently be achieved in practice.

The need to manage different source waters or impacts to distribution system

A few respondents considered that there may be some challenges associated with mixing highly treated recycled water with water from conventional sources within distribution systems. Potential issues included variations in water quality, as well as changing pressures in some sections of distribution systems.

Stranding of existing water supply infrastructure after significant investment

Two respondents thought that existing underutilised water infrastructure, namely desalination plants, should be put to use before implementing DPR.

Centralised nature of existing water supply and sewage treatment infrastructure

One respondent thought that it would be difficult to implement DPR in established urban areas with existing centralised, rather than distributed, water infrastructure.

Loss of advantage from using environmental buffer as a means of transporting or distributing water

It was noted that the advantages of some environmental buffers includes transportation or distribution to various extraction points. A DPR scheme would need to include new water distribution infrastructure to replicate these processes.

Lack of a storage buffer

The need for storage to balance supply and demand of treated water was identified. Two respondents found DPR to be lacking in storage capabilities.

Risks associated with DPR

QUESTION:
Can you identify any risks associated with DPR relative to those that apply to IPR? Please consider a broad range of risks such as environmental, social and economic risks.

Many respondents simply referred back to answers that they had already provided to earlier questions, particularly the previous question relating to 'obstacles' for DPR relative to IPR. A significant number of responses indicated that respondents could not identify any risks associated with DPR relative to those that apply to IPR. Many respondents simply answered "no" to this question while others did not provide an answer. Furthermore, some participants provided an unsolicited opinion that there are likely to be fewer risks associated with DPR compared to IPR.

Social risks

A number of respondents saw social risk as a significant management challenge because of the complexity of individual and group perceptions and reactions to DPR, as well as to water recycling more generally. However, some respondents also noted the opportunity to improve public participation and transparency in the DPR decision-making process.

Political risks

A few respondents thought that DPR was a difficult political issue that was unlikely to be championed by governments while alternative water supplies were available.

Water quality/safety/public health risks

A large number of respondents noted the public health risks associated with treatment system failures, as well as the potential for unknown long-term risks associated with consuming treated water. The environmental buffer was typically viewed as providing an important layer of safety, particularly in the context of novel chemical hazards and technology failures.

Economic risks

A number of respondents commented on the uncertain economic feasibility of implementing DPR. DPR schemes might ultimately be deemed unacceptable, leaving stranded assets. The perceived increased treatment and monitoring costs of DPR were often seen as being prohibitive.

Environmental risks

Several respondents were concerned about the environmental impacts associated with the advanced water treatment in DPR, including increased energy requirements and disposal of treatment by-products. A few respondents noted the valuable contribution that discharges into environmental buffers could make towards environmental risk management.

Other risks

Other risks identified included a potential lack of locations for storage of treated water and whether or not DPR could operate as a stand-alone option.

Knowledge gaps for DPR

QUESTION:
Are there important 'knowledge gaps' that should be addressed prior to proceeding with DPR in Australia? Please elaborate as much as possible.

A diverse range of potential knowledge gaps was identified by respondents. These included some relatively technical gaps relating to scheme design, assessment, operation and validation. Regulatory gaps and lack of information regarding economic and environmental impacts were also identified.

Water quality and process performance objectives

Two respondents believed that the existing Australian standards for water recycling were deficient in key areas including 'reliability' standards and source water management.

Treatment plant design

Three respondents stated that there were knowledge gaps regarding the treatment performance capabilities of key processes or treatment trains for the effective removal of contaminants.

Treatment plant operation

A few respondents suggested knowledge gaps or deficiencies in current AWTP operation and control. Improved training for plant operators was an identified need.

Health risk assessment

A number of respondents indicated that there are knowledge gaps in our ability to undertake comprehensive risk assessments in order to fully quantify risks posed to human health.

Assessment and management of hazardous substances in wastewater

A large number of respondents expressed concern about current levels of uncertainty in relation to the assessment and management of hazardous substances present in wastewaters. In particular, respondents identified industrial waste discharge, endocrine disrupting chemicals and hormones, radioactive and medical waste, disinfection by-products, and "undetectable/unknown contaminants".

Treatment performance and water quality validation and monitoring

A large number of respondents identified knowledge gaps relating to effective monitoring and validation of water treatment performance and water quality. In particular, respondents suggested that there was a need to better understand the capabilities, as well as the 'reliability' and 'failure modes' of key treatment processes and trains. A common recurring theme was the need for 'continuous', 'online' or 'real-time' monitoring. The improved use of surrogates and indicators, and specific toxicity tests for recycled water was suggested. One respondent suggested the need for 'demonstrated long term health and environmental studies'.

Approaches for building or assessing stakeholder acceptance

A number of respondents pointed out that there was no proactive or strategic community awareness campaign in Australia to facilitate the acceptance of DPR. Effective approaches for doing so were seen as an important knowledge gap for a large number of respondents.

Regulatory gaps

Several respondents thought that regulatory gaps created uncertainty for operators and investors. In particular, it was suggested that there remain some unresolved questions in current guideline documents including issues around the regulation of chemicals of concern and plants that are unable to provide continuous validation. Some suggested that a clear definition of what constituted DPR would be required and questioned whether existing guideline documents would remain applicable to such projects. It was noted that the development of new guidelines for DPR would be a slow process as it would require extensive national stakeholder consultation.

Environmental impacts

A few respondents though that the full range of environmental impacts of DPR were not yet adequately understood, such as potential impacts of diverting water from environment flows, energy requirements and the disposal of treatment wastes.

Mixing DPR-produced waters with other sources

Several respondents considered that the potential range of impacts associated with mixing highly treated water with traditional water supplies was poorly understood. These included issues relating to taste and odour, as well stability of disinfectant residuals. Furthermore, it was suggested that in cases where blending may occur prior to subsequent conventional treatment processes, the contribution of highly treated water may have an impact on the treatment performance of some of these processes.

Economic impacts

One respondent felt that economic feasibility of DPR had not yet been satisfactorily demonstrated.

Articulation of the need/business case

A few respondents noted that a comprehensive cost benefit analysis of DPR compared to IPR, as well as other decentralised water infrastructure options, was needed.

Water storage

Two respondents thought that DPR water storage needs had yet not been adequately quantified.

Knowledge gaps within the wider community

Several respondents felt that the community's lack of knowledge about water recycling impacted on the public acceptability of DPR. It was suggested that universities, the water industry, and governments have important, but currently unfulfilled, roles in addressing this knowledge gap. Overall, it was suggested that more information should be provided to the community in a more transparent manner.

Relevant national and international precedents

Several respondents pointed to the need for proven examples of DPR, both in Australia and worldwide.

Commitment to ongoing knowledge enhancement

One respondent felt that a commitment to continuous improvement was mandatory.

Contaminants in existing drinking water systems

One respondent suggested that a better understanding of contaminants in conventional drinking water systems would support the improvement of monitoring requirements and public education.

Decision-making processes

One respondent reported that there are knowledge gaps within our current decision-making process. It was suggested that more effective public participation in the water planning process is required, as well as an even-handed participation of 'enthusiasts' and 'skeptics'.

Skills gaps for DPR

QUESTION:
Are there important 'skills gaps' that should be addressed prior to proceeding with DPR in Australia? Please elaborate as much as possible.

Respondents identified a variety of skills gaps. One commonly identified skills gap related to the lack of adequate training of treatment plant operators. A number of respondents identified stakeholder communication and participation as areas where better community engagement skills could help overcome negative public perceptions about DPR.

DPR scheme design and implementation

Three respondents saw a need for up-skilling in the broad areas of scheme design and implementation.

Treatment plant operations

A large number of respondents saw a need to up-skill treatment plant operators in DPR. Operator training and assurance of competency were seen to be important means for managing the occurrence of 'human error' at treatment plants. Two particular areas where it was suggested that skills could be improved were risk management and emergency response.

Water distribution network management

One respondent called for better strategic modelling of the ability of drinking water networks to respond to possible incidents and emergencies.

Broader organisational skills gaps

Some respondents felt that high level expertise in water management was being shed from organisations and governments, resulting in a lack of internal resources to effectively deal with DPR schemes.

Research

Two respondents commented on skills gaps relating to research to support DPR. While the research skill-base itself was seen to be sufficient, it was suggested that the key issue was 'resources to undertake the research'.

Risk assessment and risk management

Several respondents saw a need to up-skill in areas of risk assessment and risk management for plant operators and for water managers.

Stakeholder communication, engagement, and consultation

Several respondents saw skills gaps in facilitated community education and engagement to explain DPR in a way that the public can readily understand and to change negative public perceptions about DPR.

Water quality analysis

A few respondents thought that there needed to be a greater number of accredited laboratories that could undertake the necessary water quality analysis. The need for improved analytical techniques was also identified.

Policy, planning and regulation

A few respondents reflected the view that skills in policy, planning, assessment, and regulation of water recycling could be improved.

Source management

Two respondents thought better skills were needed to deal with source control, particularly trade waste.

Technological deficiencies for DPR

QUESTION:
Are there important 'technological deficiencies' that should be addressed prior to proceeding with DPR in Australia? Please elaborate as much as possible.

A considerable number of respondents indicated that they could not identify any technical deficiencies that should be addressed prior to proceeding with DPR. Among those who could, monitoring and various aspects of risk management were the most common themes. For a smaller number, the broader uptake of DPR was seen as dependent on improved treatment technologies.

None

Several respondents did not consider that any technological deficiencies were hampering the uptake of DPR.

Treatment plant design

A few respondents suggested that improvements were required in overall plant design for local conditions. Some of these identified a need for a more sophisticated understanding of the 'multiple-barrier' approach to water quality management.

Treatment technology capabilities

A few respondents felt that water treatment technologies were not yet sufficiently advanced to provide quality assurance.

Evaluation of treatment process reliability

A few respondents felt that there was a need for improved validation technology and data to ensure the reliability of treatment process performance.

Evaluating natural treatment

One respondent felt that more research was needed to assess the benefits of natural treatment by environmental buffers. It was suggested that if this was shown to be deficient, a stronger case would be made for DPR.

Monitoring

The need for improved monitoring technologies was a common theme. A large number of respondents considered that there was a need for more sensitive and reliable real time and continuous monitoring technologies. Capabilities for monitoring a broader range of potential contaminants were also suggested. These included pathogen monitoring, chemical contaminants, and bioanalytical tools.

Risk management controls

Several respondents thought that risk management controls should be improved.

Greenhouse gas emissions

One respondent called for the carbon footprint of DPR to be closely assessed and improved.

Management of RO concentrates

A few respondents considered that the water treatment brine streams required improved management. One respondent called for the further investigation into the safety of beneficial reuse of brine.

Need for reduced-cost technologies

Two respondents felt that further technological developments were required to allow DPR to be economically feasible.

Regulator approaches
Two respondents felt that a more consistent and optimal approach to regulation was required.

Lifecycle assessment and costing
A few respondents noted the need for lifecycle accounting to evaluate the costs and benefits of DPR.

Source water control
Three respondents thought that source control could be improved.

Mixing of water from various sources
Two respondents noted that improved technologies were needed to deal with the potential issues of mixing treated water with traditional water supplies.

Social issues for DPR

QUESTION:
Are there important 'social issues' that should be addressed prior to proceeding with DPR in Australia? Please elaborate as much as possible.

A range of social issues were identified, predominantly relating to public perception, acceptance and engagement. One respondent noted that there exists little support for proper evaluation of the social science.

Negative public perception
A number of respondents nominated negative public perception as an obstacle that would need to be overcome.

Need to advance risk communication and education
Several respondents saw a need for strategic community education and improved risk communication in order to address negative community perceptions about DPR.

Lack of public trust
Several respondents noted a lack of public trust in government and industry stakeholders in DPR.

Need for improved public engagement
A large number of respondents pointed to the need for better public engagement in water planning processes. Better public engagement would involve facilitating public participation allowing for a diversity of individual and group views. There was a need to develop consistent terminology for the various components of DPR that could be readily understood by the general public.

Importance of considering community preferences and values in water supply decisions
Two respondents felt that consumer choice should be respected.

Political unease
A few respondents noted that public acceptance of DPR would be difficult to achieve unless governments adopted a consistent approach of advocating for DPR schemes.

Effective and credible regulation
Two respondents saw improved regulation of DPR as a means to address public concerns.

Need to evaluate DPR within a 'big-picture' analysis of water management philosophy

Two respondents emphasised the need to evaluate DPR within a much broader 'big picture' analysis of water management philosophy. It was suggested that some important 'overriding' philosophies, including conservation, decentralisation and the need for source separation should be subjects of greater focus.

Costs

A few respondents commented that the cost of DPR would be socially unacceptable in the current economic climate and where there would always be competing uses for taxpayer's dollars.

Public safety

Several respondents identified public safety as a social issue in itself.

Potential religious concerns

A few respondents commented that DPR might conflict with some religious beliefs and practices both in Australia and in export countries.

Equity

Two respondents noted that DPR should be implemented with social equity in mind; socioeconomics should not be allowed to determine whether or not communities were forced to accept DPR.

Critical issues to overcome for DPR

QUESTION:

In your opinion, what is the most critical single issue (if any), which will need to be overcome before DPR could become broadly accepted as an aspect of water management in Australia?

A relatively broad range of issues were identified as 'the' critical issue among the various respondents. However, the vast majority of responses referred primarily to social, rather than technical, issues. The most common responses related to public acceptance.

Current lack of evidence for need

Several respondents noted that the need for DPR had not yet been established. Most of these suggested that either improved levels of water conservation or other sources of supply would prove to be adequate for some time in most cases.

Need for public and political education and acceptance/support

A large number of respondents indicated that improved public and political acceptance were the key obstacles to DPR. Many pointed to the need for proactive community education to build support.

Media sensationalism and risk of a scare campaign

Respondents noted the ability of the media to derail DPR proposals for the sake of sensational headlines and the ease with which an effective scare campaign may be waged against DPR.

Need for improved public perception

A large number of respondents identified the key obstacle as 'public perception', including the use of terms such the 'yuck factor'.

Improved regulatory environment

Three respondents saw a need to improve the regulation of DPR before significant progress could be made.

Independence, stability, and leadership in public water bodies

Two respondents called for increased stability and leadership from public water management bodies.

Acceptance that DPR is safe and reliable

Several respondents argued that more work was required to prove the safety and reliability of DPR to the public and/or regulators.

Cost

Several respondents considered that the economic feasibility of DPR had not yet been demonstrated.

Improved public consultation and decision-making processes

Three respondents called for greater public participation and transparency in the water decision-making process.

Successful trial or demonstration project

Two respondents pointed out the need for a proven example of DPR under Australian conditions.

Need for improved source control

One respondent called for improved governance of source control.

Risk of system failure

One respondent felt that the risk of failure was too great ('inevitable') and that such a failure would undermine public confidence in water recycling generally.

Chapter 6 Water quality regulation in Australia and challenges posed by DPR

Australia currently has well-developed frameworks for managing risks associated with the supply of drinking water and recycled water. These frameworks are broadly accepted by relevant industry, as well as environmental and public health regulators. However, these frameworks were generally not developed with the likely possibility of having to encompass DPR as an option for water supply and management. As such, it is necessary to consider whether the current frameworks are both compatible and sufficient to account for this non-conventional approach to water resource management.

Australian water quality guidelines developed since 2004 have exhibited a significant philosophical departure from the traditional focus on 'end point monitoring' as a means of water quality compliance. Instead, they have adopted a 'risk management' approach, also embodied in the World Health Organization Guidelines for Drinking Water Quality and the Water Safety Plans described therein. This approach emphasises the assessment and management of possible means by which contaminants may be introduced to water, and preventative measures for minimising such contamination. With reduced emphasis on end-point monitoring, Australian regulations have focused on the implementation of risk management plans. Nonetheless, some jurisdictions have required some schemes, particularly planned potable water recycling projects, to undertake comprehensive monitoring for specific chemicals and pathogens. This has led to the collection of large volumes of data for these schemes.

Australian Drinking Water Guidelines

The *Australian Drinking Water Guidelines* (ADWG) provides a framework for the management of drinking water quality in Australia (NHMRC & NRMMC 2011). A key component of the framework is systems analysis and management, which involves understanding the entire water supply system, the hazards and events that can compromise drinking water quality, and the preventive measures and operational control necessary for ensuring safe and reliable drinking water.

The ADWG provide the following key definitions for a water quality risk management context:

- a **hazard** is a biological, chemical, physical or radiological agent that has the potential to cause harm;
- a **hazardous event** is an incident or situation that can lead to the presence of a hazard (what can happen and how); and
- **risk** is the likelihood of identified hazards causing harm in exposed populations in a specified timeframe, including the severity of the consequences.

The ADWG accept that realistic expectations for hazard identification and risk assessment are important and that rarely will enough knowledge be available to complete a detailed quantitative risk assessment. Instead, the guidelines have adopted a risk prioritisation process, adapting the risk matrix approach presented in the risk management guidelines published by Standards Australia & Standards New Zealand (2004). A likely outcome of such risk assessments is the identification of specific areas where further information and research is required.

Health-based concentration guidelines are provided for a large number of organic and inorganic chemicals. These represent concentrations that, based on present knowledge, do not result in any significant risk to the health of the consumer over a lifetime of consumption. Guideline values for chemical substances were derived using human data where available or, in most cases, by using animal data adjusted by appropriate safety factors for extrapolation to humans.

The ADWG explicitly recognise that pathogenic substances present the greatest threat to the safety of drinking water supplies. However, there is currently only one water quality stipulation for monitoring of microorganisms. This is that *Escherichia coli (E. coli)* should not be detected in a 100mL-minimum-volume sample of drinking water. If detected, immediate corrective action must be taken. Although most *E. coli* are non-pathogenic, the intention is that the absence of this abundant faecal organism is an indication that drinking water treatment processes and protection of distribution systems have been effective. As such, the role of *E. coli* is for verification of effective management.

It is now well established that some waterborne pathogens are more resistant to particular common drinking water disinfection processes (e.g. chlorination) than *E. coli*. Therefore, monitoring of *E. coli* serves as a useful verification of the disinfection process, but cannot be relied upon entirely. Instead, water quality and safety is maintained by the use of identified 'critical control points' (CCPs), which are steps, processes or procedures that control significant hazards. A number of CCPs have been determined, based on their established relationship to effective pathogen control. CCPs can include a range of treatment (e.g. disinfection) and non-treatment (e.g. catchment management) barriers. Continuous monitoring of CCPs is preferred where possible.

The reliance upon CCPs is a departure from a traditional 'endpoint monitoring' approach to water quality management and represents a crucial component of the overall 'risk management' approach. It is widely supported within the Australian water industry and by public health regulators.

Health based targets for microbial water quality and risk

Although the risk management approach for drinking water quality has been effective and is widely supported, there is a growing acceptance in the Australian water industry that further development of this approach is warranted in the near future. In particular, it has been recognised that specific maximum levels of 'acceptable' or 'tolerable' risk from pathogens must be identified and targeted for achievement by drinking water providers. As such, the water industry and its regulators are currently working towards the development of 'health based targets' for microbial water quality. Exactly how these targets will be applied is yet to be determined, but it is likely that they will develop along the lines of the approach already taken in the Australian Guidelines for Water Recycling – Phase 1 (NRMMC, EPHC & AHMC 2006).

Australian Guidelines for Water Recycling – Phase 1

Phase 1 of the Australian Guidelines for Water Recycling was published in 2006 by the National Resource Management Ministerial Council and the Environment Protection and Heritage Council (2006). Phase 1 does not cover the development or management of potable water recycling schemes: it provides guidance on managing the health and environmental risks associated with the use of recycled water for non-potable applications.

Nonetheless, these guidelines are notable for the risk management framework that they provide, rather than simply relying on end-product recycled water quality testing as the basis for managing water recycling schemes. The risk management framework used in the guidelines is based on the framework detailed in the ADWG (NHMRC & NRMMC 2011). However, an important further development is that the water recycling guidelines promote a quantitative assessment of health-based risks, with a strong focus on risks from pathogens.

In managing risks from pathogens to human health, the guidelines provide a numerical definition of safety. Specifically, they use disability adjusted life years (DALYs) to convert the likelihood of infection or illness into burdens of disease, setting a tolerable risk as 10^{-6} DALYs per person per year. The tolerable risk is then used to set health-based targets that, if met, will ensure that the risk remains below 10^{-6} DALYs per person per year.

DALYs for a disease or health condition are calculated as the sum of the Years of Life Lost (YLL) due to premature mortality in the population and the Years Lost due to Disability (YLD) for incident cases of the health condition, as shown below:

$$\text{DALYs} = \text{YLL} + \text{YLD}$$

Where YLL = N × L such that N is the number of deaths and L is the standard life expectancy in years at the age of death, and YLD = I × DW × D such that I is the number of incident cases, DW is the weighting ascribed to the 'disability', and D is the average duration of the condition in years until remission or death.

As an example, infection with rotavirus causes mild diarrhoea (disability weighting of 0.1) lasting three days in 97.5% of cases; severe diarrhoea (disability weighting of 0.23) lasting seven days in 2.5% of cases; and rare deaths of very young children in 0.015% of cases. The number of DALYs per case of rotavirus infection are then given as follows:

$$\text{DALYs per case} = (0.00015\times80)+((0.975\times0.1\times3/365.25)+(0.025\times0.23\times7/365.25))$$
$$\text{DALYs per case} = 0.012 + 0.0008 + 0.0001$$
$$\text{DALYs per case} = 0.0129$$

One DALY can be thought of as one lost year of 'healthy' life. The sum of these DALYs across the population – the burden of disease – can be thought of as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability.

If source water quality is known, and risks of exposure can be properly characterised using dose-response relationships and other factors such as existing immunity in the community, then it is possible to set 'system performance targets' based on reaching the 'tolerable burden of disease', 10^{-6} DALYs per person per year.

The practical application of this approach is focused on three carefully selected 'reference pathogens' representing enteric viruses (a combination of rotavirus and adenovirus), bacteria (*Campylobacter jejuni*) and protozoa (*Cryptosporidium parvum*). Assessment of raw water concentrations of these reference pathogens, and determination of the relationship between exposure and DALYs lost, enables the determination of overall treatment process performance to ensure that exposure in finished water is below the levels corresponding to 10^{-6} DALYs per person per year.

This health-based target approach to recycled water quality has required, and continues to require, the initiation of a number of research activities to support decision-making and regulation. In particular, there has been a need to develop techniques for performance validation of various water treatment processes, including physical, biological and chemical treatment processes. It is anticipated that, as this knowledge continues to increase, confidence in recycled water safety will increase accordingly.

Among the advantages of the health-based targets approach are that water recycling schemes are afforded a high degree of flexibility in their design. The use of specific treatment technologies, or conditions such as minimum travel times in aquifers, is not stipulated. This accommodates future developments in technology and the consideration of unique characteristics of specific projects. Furthermore, it ensures that the key design feature of all schemes is explicitly identified as the satisfactory protection against public health risks.

Australian Guidelines for Water Recycling – Phase 2

Phase 2 of the *Australian Guidelines for Water Recycling* consists of three modules that specifically address stormwater use (Natural Resource Management Ministerial Council *et al.*, 2009b), managed aquifer recharge (Natural Resource Management Ministerial Council *et al.*, 2009a), and augmentation of drinking water supplies (NRMMC, EPHC & NHMRC 2008). The module for the augmentation of drinking water supplies, in particular, provides risk management guidance for chemical and pathogenic contaminants in addition to that which was provided in the Phase 1 guidelines.

Consistent with the Phase 1 guidelines, the Phase 2 guidelines use DALYs as a measure of risk associated with pathogenic organisms and apply a tolerable risk of 10^{-6} DALYs per person per year.

The approach uses the following reference pathogens: *Cryptosporidium* for protozoa and helminths, a rotavirus and adenovirus combination for enteric viruses, and *Campylobacter* for bacteria. The default 95th percentile concentrations for these organisms per litre of sewage are given as 2000 *Cryptosporidium*, 8000 rotavirus and 7000 *Campylobacter*. Using these values, and an average daily consumption of two litres per person per year, the log reductions required to achieve compliance with 10^{-6} DALY per person per year can be calculated using the formula:

$$\text{Log reduction} = \log((\text{source concentration} \times 2 \text{ litres} \times 365 \text{ days})/\text{DALYd})$$

Where DALYd (the dose equivalent to 10^{-6} DALYs) is 1.6 $\times10^{-2}$ for *Cryptosporidium*, 2.5 $\times10^{-3}$ for enteric viruses, and 3.8 $\times10^{-2}$ for *Campylobacter*.

The minimum log reductions required for production of drinking water from sewage are therefore determined to be:

- *Cryptosporidium* – 8 orders of magnitude;
- Enteric viruses – 9.4 orders of magnitude; and
- *Campylobacter* – 8.1 orders of magnitude.

A combination of treatment processes is required to cumulatively achieve these log reductions. In order to receive credit for them, individual schemes are required to validate the performance of treatment processes against the log reduction values (LRVs) that they are reported to achieve. As a rule, regulators will only credit treatment processes with the maximum LRVs that can be continuously and reliably monitored. Nonetheless, the guidelines provide a range of 'indicative log reductions' that may be achieved for various organisms by various treatment processes. Most notably, the indicative LRVs (less than 6 for all indicator organisms) attributed to reverse osmosis are rarely credited by regulators, due to the unavailability of sufficiently sensitive continous monitoring techniques. Monitoring RO performance by common techniques such as conductivity, turbidity and total organic carbon, tends to limit verified pathogen removal to around 2 LRVs.

The approach adopted for chemicals is based on that of the ADWG where the tolerable risk is implemented through the development of corresponding guideline values. For chemicals with threshold toxicities, the guideline values generally correspond to identified No Observed Adverse Effect Levels or Lowest Observed

Adverse Effect Levels with applied uncertainty factors. For non-threshold toxicity chemicals, such as carcinogens, guideline values are based on the 1 x 10^{-6} cancer risk following lifetime consumption, defined as 70 years.

Chemical guideline values are tabulated in the guidelines along with maximum concentrations of the chemicals that have been reported from studies of secondary or tertiary treated sewage effluent. This has been compiled from a range of Australian and international datasets. However, the guidelines note that the table should not be taken as exhaustive and that detailed assessment of individual systems – including surveys of industrial, agricultural, domestic and urban inputs – should be undertaken to identify potential chemical hazards that could affect source water quality. In most cases, this assessment will need to be supported by extensive monitoring.

The health-related guideline values for chemicals have been acquired or derived from various sources as described in Appendix A of the Phase 2 guidelines. Where possible, guideline values were acquired from existing guidelines and standards, with the ADWG being the primary source. Where no existing guideline values could be identified, guidelines were developed from available health, toxicological or structural information.

Guidelines for dioxins, furans and polychlorinated biphenyls, PCBs, were developed using National Health and Medical Research Council recommended tolerable intakes that account for the combined total exposure for multiple chemicals. Using toxicity equivalency factors as evaluated by the World Health Organization (WHO) (Van den Berg *et al.*, 2006), a total concentration guideline value of 0.016 nanograms per litre toxicity equivalents was determined for this group of chemicals.

Guideline values for human pharmaceuticals were derived from lowest daily therapeutic doses divided by uncertainty factors of 1000–10,000. Guidelines for pharmaceuticals used for agricultural or veterinary purposes were developed from acceptable daily intake values established by a range of international food and health agencies.

Where neither existing guidelines nor relevant toxicological data to develop guidelines was available, a quantitative structure-activity relationship approach was used as method for determining thresholds of toxicological concern (TTCs). The use of TTCs is well established internationally and has been applied by the United States Food and Drug Administration and the WHO for setting guidelines for minor chemical contaminants (WHO 1987; FDA 2006).

The guidelines note that an extensive range of parameters can be used to represent a risk. They acknowledge that it is not physically or economically feasible to test for all parameters, nor is it necessary. The list of guideline values is not intended to be regarded as a mandatory set of parameters to be included in monitoring programs. However, key characteristics that must be considered for system performance verification include:

- microbial indicator organisms;
- health-related chemicals, including:
    - those identified in the ADWG;
    - key organic chemicals of concern (for example, NDMA);
    - indicators or index chemicals for organic chemicals (for example, contraceptive hormones); and
- biological activity

The choice of specific parameters must be informed by hazard identification and risk assessment. These, in turn, should be informed by consideration of source water quality, potential agricultural and industrial inputs, treatment processes, chemicals and by-products, and receiving water quality.

DPR and the Australian regulatory system

The Framework for Managing Drinking Water Quality underpins the *Australian Drinking Water Guidelines* and also forms the basis of the risk management framework adopted in the Australian Guidelines for Water Recycling. This Framework is intentionally non-prescriptive regarding the design of water supply systems and does not impose specific requirements such as treatment technologies that should be employed. Part of the philosophy of the Framework is to acknowledge that all drinking water supply systems are unique and that one of the keys to safe drinking water management is to 'know your system'. The Framework promotes a risk assessment and risk management process that involves understanding how key barriers of a multiple barrier water supply and treatment system function, as well as their potential vulnerabilities in the face of 'hazardous events'. There is no fundamental characteristic of a well-designed and managed DPR scheme that renders the Framework less applicable relative to any other conceivable water supply system. Accordingly, there appears to be no serious ideological or philosophical leap required in Australia in order to move from an acceptance of IPR to an equal acceptance of DPR.

Nonetheless, the Phase 2Australian Guidelines for Water Recycling cast a cautionary tone on the potential future of DPR in Australia (NRMMC, EPHC & NHMRC 2008):

> *Direct augmentation using recycled water derived from highly treated sewage or stormwater means that recycled water enters the recycling system without going through an intermediary receiving body of water. Unless large treated-water storages are included in systems, the time between the recycled water starting treatment and being distributed through drinking water systems could be hours. Thus, the scope for assessing water quality and intervening before substandard water is supplied to consumers is limited. Direct augmentation should not proceed unless sufficient mechanisms are established to prevent substandard water from being supplied. Implementation of direct augmentation presents substantial technical and management challenges. The need for reliability of processes, vigilance of monitoring and highly skilled operators – already high for indirect use – is magnified for direct augmentation. Knowledge and understanding of system reliability and control of variability is essential before direct augmentation can proceed. Further research is required in this area.*
>
> *Replacing the benefits of receiving waters with additional engineered treatment barriers or large treated-water storages comes at a high cost. In addition, community acceptance of direct augmentation, particularly with treated sewage, will be difficult to achieve. Only one direct use scheme is currently in operation. That scheme was introduced at Windhoek, Namibia in the 1960s, and no others have been introduced since that time.*

The "substantial technical and management challenges" described here are indeed real. However, it is appropriate that the guidelines do not "disallow" DPR. The overriding philosophy for water management in Australia is increasingly focused on the demonstrated achievement of safe water supply, without prescription of the precise means by which that is achieved. It would be inconsistent with this approach to rule that a potable water reuse project must necessarily incorporate an environmental buffer when an equivalent level of safety could be achieved using engineered processes only.

The responsibility for demonstrating and assuring that a DPR scheme could achieve a required level of safety would fall largely on the proponent of such a project. The terms of that demonstration and assurance would be dictated largely by the State-based health regulatory agency. However, were they to be adhering to the letter and spirit of the Framework for Managing Drinking Water Quality, there appears no reason to presume that such a scheme could not be approved.

Nonetheless, it can be assumed that regulatory authorities would seek a higher level of assurance for the safety and reliability of a DPR project, compared to IPR. In particular, regulators may be expected to seek assurance that the loss of 'time to respond' can be effectively managed without presenting significantly increased risks to public health. Such assurances could conceivably be provided with well-designed engineered storages and by the incorporation of appropriate monitoring and response protocols. These could include the ability to shut down production, dispose or re-treat water that does not meet quality assurance requirements or, in some cases, the application of additional disinfection.

An essential aspect of the Phase 2 Australian Guidelines for Water Recycling that could not be dispensed with is the list of key principles described therein. It is stated that adherence to these key principles is 'fundamental to safe augmentation of drinking water supplies' (NRMMC, EPHC & NHMRC 2008). These include:

- protection of public health is of paramount importance and should never be compromised;
- drinking water augmentation requires community acceptance and support;
- institutional capacity is required;
- recycled water systems need to include and continuously maintain robust and reliable multiple barriers;
- designers, operators and managers of schemes must have appropriate skills and training;
- system operators must be able to respond quickly and effectively to adverse monitoring signals;
- industrial waste management programs need to be established and maintained;
- all schemes must be subject to regulatory surveillance;
- the greatest risks to consumers of drinking water are pathogenic microorganisms; so protection of water sources and treatment are of paramount importance and must never be compromised; and
- any sudden or extreme change in water quality, flow or environmental conditions (e.g. extreme rainfall or flooding) needs to arouse suspicion that drinking water might become contaminated.

Chapter 7 Health risk assessment and risk management

Among the key issues to be addressed for any proposed DPR project are the satisfactory assessment and management of health risks. Following the frameworks set out in Australian water quality guidelines, as described in Chapter 6, this will involve the identification of potentially hazardous substances and incorporation of 'barriers', such as treatment processes, to control exposure of people to these hazards.

As with all municipal water recycling projects, contaminants of concern encompass a wide variety of pathogenic microbial organisms and chemical contaminants, which may be present in conventionally treated municipal effluents. Their presence is generally considered to be of concern due to their potential deleterious impacts to human health.

When considering health risks posed by water contaminants, an important distinction is made between acute and chronic exposure risks. Acute exposure risks relate to potential health impacts from short-term exposure and, for chemicals, are usually associated with high doses. Chronic exposure risks relate to ongoing or long-term exposure and may often be associated with much lower doses. The concentrations of toxic chemical substances in water are rarely sufficient to present acute risks and most health concerns (for example, cancer) are associated with chronic exposure. In contrast, pathogens most commonly present acute risks, whereby illness may develop immediately following exposure.

This distinction between acute and chronic exposure risks has important implications for risk assessment and risk management. Failure of a chemical removal process that results in increased exposure to chemicals will likely not result in an adverse health impact, assuming the failure is identified in a matter of hours or days. However, this is not the case for pathogens, where short term exposure can result in adverse health impacts. As such, many risk management considerations (for example, capabilities for continuous monitoring, time to respond, and engineered treatment redundancy) tend to be much more important for pathogens than they are for chemicals.

Pathogens

The control of pathogenic organisms is fundamental to the protection of public health for all potable water supplies. However, in the case of potable reuse, where municipal wastewaters comprise a major component of source waters, presence of significant initial concentrations of pathogens can generally be assumed. In terms of their ability to contaminate drinking water supplies and their infectivity, the most significant human pathogens in untreated sewage include a range of bacteria (for example, *Campylobacter*, *Shigella* and *Salmonella*), viruses (for example, rotaviruses, adenoviruses, noroviruses and Hepatitis A) and protozoan parasites (for example, *Cryptosporidium* and *Giardia*).

The diversity and concentrations of pathogens in treated wastewater effluents is highly variable and dependent upon numerous locally specific factors. These factors include the patterns of infection within the community and the type of secondary and tertiary treatment, as well as disinfection processes, employed at the wastewater treatment plant.

Waterborne bacteria tend to be relatively susceptible to chemical disinfection (for example, chlorination and chloramination) and can therefore be effectively controlled by wastewater reclamation processes. Accordingly, bacteria tend not to be a primary concern or driver of the implementation of advanced treatment processes in potable reuse schemes.

Viruses are widely recognised as the microorganisms representing the most significant risks to public health from potable reuse projects. Although they are generally susceptible to inactivation by chlorine disinfection, their high concentration in municipal wastewaters (Costan-Longares *et al.*, 2008) and high infectivity require careful management to maintain adequate levels of disinfection. As such, effective virus removal to achieve assigned health based targets (see Chapter 6) is commonly a major determinant of treatment requirements for potable reuse projects. Effective monitoring presents an additional challenge to virus control since few laboratories possess the necessary expertise for proper analysis.

Enteric protozoan parasites are notorious agents of waterborne disease and are commonly associated with reported outbreaks. *Cryptosporidium* in particular is reported to have been the cause of illnesses, and sometimes deaths, from drinking water supplies with full conventional treatment (coagulation/flocculation, granular media filtration, and chlorine disinfection), usually under challenging or erroneous circumstances (Hrudey & Hrudey, 2007). Some protozoa may be excreted as cysts or oocysts that aid in their survival. As a result, some of these organisms, including *Cryptosporidium*, are highly resistant to chlorine disinfection and must generally be controlled by other means, such as ultraviolet light disinfection, ozone oxidation, or membrane filtration.

Chemical substances

The overall load of dissolved organic chemicals in water can be quantified in terms of the dissolved organic carbon concentration. DOC in municipal wastewater effluents is comprised of natural organic matter (originating from drinking water), soluble microbial products (generated during the activated sludge process), and small concentrations of a very large range of organic chemical contaminants. These contaminants can include industrial and domestic chemicals (for example, pesticides, personal care products, preservatives, surfactants, flame retardants, perfluorochemicals, nanoparticles), chemicals excreted by humans (for example, pharmaceutical residues, steroidal hormones), as well as chemicals formed during wastewater and drinking water treatment processes (for example, disinfection by-products).

Chemical contaminants may be present in reclaimed source waters, or may be formed as by-products or metabolites via chemical or biological transformation during wastewater collection and treatment. Many of these chemicals may have an adverse effect on human health if they are present in sufficient quantities, not effectively removed during treatment, and exposure occurs over a sufficient period. Potential chronic adverse health effects include carcinogenic, toxicological, embryonic and reproductive development impacts caused by interference with the endocrine system.

Depending on the catchment area, and the extent of the trade waste program to control chemicals at the wastewater source, a very wide range of synthetic industrial chemicals is often measurable in urban municipal wastewater. Examples include plasticisers and heat stabilisers, biocides, epoxy resins, bleaching chemicals and by-products, solvents, degreasers, dyes, chelating agents, polymers, polyaromatic hydrocarbons, polychlorinated biphenyls and phthalates. Many of these chemicals are known to be toxic to a diverse range of organisms, including humans.

Pharmaceuticals and their active metabolites are excreted to sewage by people, as well as through direct disposal of unused drugs by households (Shon *et al.*, 2006). Since pharmaceuticals are designed to instigate biological responses, their inherent biological activity and the diverse range of compounds identified in sewages and the environment have been cause for considerable concern during the past decade. A broad range of pharmaceutically active compounds has been reported in US drinking water as a consequence of unplanned indirect potable reuse (Benotti *et al.*, 2009).

Natural steroidal hormones such as oestradiol, oestrone and testosterone are also excreted to sewage by people. During the last two decades, natural steroidal hormones have been widely implicated in a range of endocrinological abnormalities in aquatic species that are affected by sewage effluent. However, despite widespread concern, there is currently scant evidence to directly link environmental exposure to these chemicals with impacts on human health.

An important group of emerging environmental contaminants of concern is nanoparticles or nanomaterials. These are commonly defined as particles between about 1 and 100 nanometres in diameter that show properties that are not found in bulk samples of the same material. The toxicological concerns for nanoparticles are related not only to their chemical composition, but also to physical parameters including particle size, shape, surface area, surface chemistry, porosity, agglomeration tendency and homogeneity of dispersions (Hussain *et al.*, 2009). As such, it is increasingly recognised that traditional techniques for toxicological and ecotoxicological evaluation of chemical substances are not well applied to the evaluation of nanoparticles.

Disinfection by-products

Disinfection by-products are formed by reactions between disinfection agents and other constituents of water (Richardson *et al.*, 2007; Deborde & von Gunten, 2008). High initial concentrations of organic components may lead to excessive production of certain DBPs in the absence of high ammonia concentrations. Similarly, the presence of ammonia in some source waters may lead to the formation of nitrogen-containing DBPs. The vast majority of the compounds of concern originate from chlorine-based disinfectants. Accordingly, excessive formation of well-known DBPs, such as trihalomethanes and haloacetic acids, must be carefully monitored and controlled.

Ozone treatment of reclaimed water may result in the formation of several groups of DBPs including bromate and carbonyl compounds, such as aldehydes. Bromate is a suspected human carcinogen and some aldehydes, including formaldehyde and acetaldehyde, have been classified as probable human carcinogens by the US EPA.

Advanced oxidation processes utilise the transient formation of hydroxyl radicals to degrade carbon-carbon and other chemical bonds. The range of by-products formed is a function of the nature of the organic matter present and the relative susceptibility of specific bonds to attack by radical species. Accordingly, a large number of unidentified low molecular weight products may be expected to be formed during advanced oxidation of complex solutions. On the other hand, effective pre-treatment, such as by reverse osmosis, can produce water with very low concentrations of organic material for the formation by-products.

Ammonia can occur in wastewater effluents, either as a result of incomplete nitrification or by controlled addition for the purpose of chloramination. The presence of ammonia and suitable organic precursors can lead to the production of N-nitrosamines, such as N-nitrosodimethylamine (NDMA) and N-nitrosodiethylamine (NDEA). Some N-nitrosamines, including NDMA and NDEA, have been classified as probable human carcinogens. The N-nitrosamines tend to warrant particular scrutiny in potable reuse projects since some (most notably NDMA) are relatively poorly removed by reverse osmosis.

Microbial indicators

It is not possible to directly monitor all potentially pathogenic microbial organisms. This is for a variety of reasons, including the broad diversity of species and strains that may be present. Furthermore, pathogen monitoring tends to be a relatively slow process – some tests can be completed in hours, but many may take days. Due to the risks involved, pathogen testing is undertaken in a carefully controlled, specialised laboratory setting and is generally very expensive to perform.

The approach taken for recycled water systems is to monitor for a set of carefully selected 'indicator organisms'. The Australian Guidelines for Water Recycling provide detailed information pertaining to the use of microbial indicators for validation, monitoring and management of health risks in recycled water (NRMMC, EPHC & AHMC 2006). The guidelines also provide a substantial review of log reductions of enteric pathogens and indicator organisms for a number of water treatment barriers.

The applicability of quantitative microbial risk assessment for the management of water reclamation schemes depends on reliable measurement of the effectiveness of barriers such as disinfection and filtration by studying the behaviour of microbial indicators. Traditionally, microbial indicators have been used to suggest the presence of pathogens (Fewtrell & Bartram, 2001), but today we understand a multitude of possible reasons for indicator presence and pathogen absence, or vice versa (Fewtrell & Bartram, 2001). To eliminate the ambiguity in the term 'microbial indicator', the following three groups presented in Table 3 are now recognised.

Table 3 Definitions for indicator organisms of public health concern (Fewtrell & Bartram, 2001)

Group	Definition
Process indicator	A group of organisms that demonstrates the efficacy of a process such as total heterotrophic bacteria or total coliforms for chlorine disinfection.
Faecal indicator	A group of organisms that indicates the presence of faecal contamination, such as the bacterial groups thermotolerant coliforms of *E. coli*. Hence, they only imply that pathogens may be present.
Index and model organisms	A group/or species indicative of pathogen presence and behaviour respectively, such as *E. coli* as an index for *Salmonella* and F-RNA coliphages as models of human enteric viruses.

Levels of microbial indicators must be more conservative than for their representative pathogen, or demonstrate a reliable relationship between the indicator organism and the target pathogen (NRMMC, EPHC & AHMC 2006).

The behaviour of different types of pathogens needs to be considered when selecting an indicator, as it is unlikely that a single indicator will be representative of all pathogens (Keegan *et al.*, 2009). Therefore, indicator selection needs to be tailored to the pathogens and removal mechanisms of interest. For example, yeast cells can be used as a surrogate to assess the efficacy of a processes ability for physical removal of protozoan cysts (e.g. by filtration), but are not suitable for validating biological or disinfection processes due to differing levels of resistance. The ideal indicator must therefore mimic the behaviour and characteristics of a pathogen, but also be easier, faster and cheaper to enumerate, and be non-pathogenic (Keegan *et al.*, 2009).

Process indicators are often favoured in validation studies in place of infectious pathogens because of the following advantages:

- in sewage, indigenous microbial indicators are typically non-seasonal, and are present in higher numbers than pathogens to demonstrate high magnitude log reduction;
- if challenge testing is required, indicators can be easily cultured in high densities without high

containment standards. Conversely, several pathogens of concern (noroviruses, rotaviruses, *Cryptosporidium*, *Giardia*, *Coxiella*, *Leptospira*, *Mycobacterium* spp.) either cannot be cultivated, grow very slowly, or their cultivation requires high containment standards;

- cost effectiveness of monitoring is a significant factor. Indicators are favoured because they are affordable (e.g. compare the analytical cost of *Clostridium perfringens* versus *Cryptosporidium* spp.), which allows more tests than pathogen testing and thus more reliable assessment of process variability; and
- enumeration techniques are fast, sensitive, reproducible and easy to perform. Conversely, pathogen results can be misleading if the methods used do not meet the quality assurance and quality control requirements.

A review of target pathogens for common treatment processes and potential surrogates is provided in the Victorian Guidelines for validating treatment processes for pathogen reduction (Department of Health Victoria, 2013) and also UK Water Quality Guidelines (Fewtrell & Bartram, 2001). Examples include:

- Clostridia (for example, *C. perfringens*, *C. sporogenes*)
  Spore formers have been used as convenient surrogates of protozoan pathogen inactivation (Venczel *et al.*, 1997; Facile *et al.*, 2000) and their high resistance to environmental stressors makes them a conservative model for assessing the performance of secondary treatment processes (for example, activated sludge). However, correlation with protozoa has not been consistent (Keegan *et al.*, 2009).
- Bacteriophage
  Somatic DNA Coliphage and F-specific RNA Coliphage (FRNA phage) are widely used as indicators of enteric virus behaviour. They are present in high concentrations in sewage and have been proposed as indicators of virus removal in water treatment processes (Marti *et al.*, 2011). The US Environmental Protection Agency recommends the use of a specific bacteriophage, MS2, for the evaluation of membranes (US EPA 2005). Although they are often seen as a conservative virus model for the validation of membranes, Ottoson *et al.* (2006) showed that they were more easily removed in biological nutrient removal processes than the human virus genomes. UV light irradiation systems are validated using MS2 (US EPA 2006).
- Virus genomes
  Analysis for virus genomes using polymerase chain reaction (PCR) technologies has been widely used to assess viral concentrations. The techniques are well established and, for non-culturable viruses like rotavirus and norovirus, they are the first choice. However, PCR-based methods do not determine viable infective particles and generally overestimate concentrations (Keegan *et al.*, 2009). They can be useful for measuring effectiveness of short duration physical removal processes where inactivation will be limited.
- Vegetative bacteria
  Bacterial indicators, including *E. coli*, enterococci and *Bacteroides* spp. are all present in high numbers in sewage and are representative of common bacterial pathogens (Keegan *et al.*, 2009). *E. coli* is considered to be an important bacterium to the water industry, primarily as an indicator organism for the detection of faecal contamination and also as a cause of water-borne outbreaks.
- Particle profiling
  Particle profiling has been reported as a useful indicator for the removal of helminths from wastewater, with a high correlation observed between numbers of helminth ova and the volume of particles of 20 to 80 microns (Keegan *et al.*, 2009).
- Fluorescent dyes
  Rhodamine WT dye is considered a practical surrogate for detecting imperfections in RO membranes relative to virus removal. However, it is limited to a sensitivity of 4 log (Department of Health Victoria, 2013). Log reduction values can also be limited by the low feed concentration.

A trade-off exists between the use of high dye feed concentration to demonstrate high LRV and adsorption and/or accumulation of dye on the membrane surface that could result in fouling. Rhodamine WT was used for validating pathogen removal at the Gippsland Water Factory in Victoria. That study showed that when dosed at a concentration of 100 µg/L, an intact 2-stage RO system could achieve approximately 2.6 log dye removal with removal most likely limited by feed dye concentration.

- Microspheres
  Microspheres have been proposed as a surrogate to protozoa and viruses for assessing microfiltration and ultrafiltration membrane performance. However, if surface charge and other characteristics are not properly considered, using microspheres as surrogates for microorganisms may yield inconsistent results where the rejection mechanism is by adsorption, adhesion, or where electrostatic considerations are important, rather than by simple size exclusion (Pontius *et al.*, 2009).

Chemical indicators

As is the case for microbial organisms, it is never possible to directly measure the concentrations of all potential hazardous chemicals in a recycled water system. Therefore, a similar approach to the use of microbial indicators, based on chemical indicators, has been developed (Drewes *et al.*, 2008).

In this context, an *indicator compound* is an individual chemical occurring at a quantifiable level which represents certain physicochemical and/or biodegradable characteristics of a larger group of trace constituents. The representative characteristics must be relevant to the transport and fate of the indicator compound, as well as the larger represented group of constituents, providing a conservative assessment of removal. A *surrogate parameter* is a quantifiable change of a bulk parameter that can serve as a performance measure of individual unit processes or operations regarding their removal of trace compounds.

Physicochemical properties (for example, molecular size, acidity constant (pK_a), octanol-water partition coefficient (log K_{ow}), volatility and dipole moment) often determine the fate and transport of a compound during various treatment processes such as high-pressure membranes (Bellona *et al.*, 2004). Thus, the judicious selection of multiple chemical indicators, representing a broad range of physicochemical properties, enables the assessment to account for compounds that may not be currently identified, 'unknowns', as well as new compounds synthesised and entering the environment in the future (for example, new pharmaceuticals), provided they fall within the range of the properties covered by the indicators.

The underlying assumption is that absence or removal of an indicator compound during a treatment process would also ensure absence or removal of other compounds with comparable physicochemical properties. The most sensitive compounds to assess the performance of a specific treatment process will be those that are partially removed under normal operating conditions. Thus a system failure will be indicated by poor removal of the indicator compound while normal operating conditions will be indicated by partial or complete compound removal.

Predetermined changes of surrogate parameters can be used to define and assure normal operating conditions of a treatment process. Proper removal is ensured as long as the treatment process of interest is operating according to its technical specifications. It is therefore necessary to define, for each treatment process, the operating conditions under which proper removal is to be expected (Drewes *et al.*, 2008).

Potential indicator compounds and surrogate parameters have been identified for a range of conventional and advanced water treatment processes (Drewes *et al.*, 2008). These treatment processes have then been characterised by key removal mechanisms, such as biodegradation (managed aquifer recharge), chemical oxidation (ozonation, advanced oxidation, chlorination and chloramination), photolysis (low pressure

UV radiation), adsorption (granular activated carbon treatment) or physical separation (nanofiltration and reverse osmosis).

Surrogate parameters are often not strongly correlated with the removal of indicator compounds occurring at concentrations in the order of nanograms per litre (Drewes *et al.*, 2008). However, partial or complete change of carefully selected surrogate parameter removal can demonstrate the proper performance of a unit operation or treatment train. Some surrogate parameters are also sufficiently sensitive to indicate the beginnings of performance deficiencies, which may or may not be resulting in a diminished removal of contaminants of toxicological concern. Thus, to fully assess the performance of unit operations, a combination of appropriate surrogate parameters and indicator compounds should be used.

Performance assessment of individual unit processes comprising an overall treatment train are distinguished into two phases: *validation monitoring* during piloting or commissioning; and compliance monitoring during full-scale operation (defined as *operational and verification monitoring*). The individual steps followed in tailoring such a monitoring program are outlined in Table 4.

Table 4 Application of the surrogate/indicator framework to an overall treatment train (Drewes *et al.*, 2008).

	Surrogate parameters	Indicator compounds
Validation monitoring: piloting or commissioning		
Step 1	Define and verify operational boundary conditions for each unit process comprising the overall treatment train after operating the system assuring steady-state conditions. Do operational boundary conditions meet design criteria within an acceptable range? If yes, proceed to step 2. If not, determine cause for deviation.	Baseline monitoring: Conduct occurrence study to confirm presence of viable indicator compounds in the feedwater of each unit process.
Step 2	Quantify surrogate rejection of overall system, e.g. conductivity. Is conductivity rejection within previously observed range and does it meet performance specification of manufacturer? If yes, proceed to step 3. If not, determine cause for deviation, for example by quantifying conductivity rejection of individual vessels.	Identify 5 to 10 suitable indicator compounds for spiking study (challenge test).
Step 3	Validation monitoring: Quantify removal differential of viable surrogate parameter: $\Delta X_i = (X_{i-in} - X_{i-out}) / X_{i-in}$	Validation monitoring: Conduct spiking study with selected indicator compounds (5 to 10) to determine the removal differentials under pre-determined operating conditions: $\Delta Y_i = (Y_{i-in} - Y_{i-out}) / Y_{i-in}$
Step 4	Select viable surrogate and operational parameters for each unit process.	Select 3 to 6 indicator compounds from categories classified as 'Good removal'.
Compliance monitoring: full-scale operation		
Step 5	Confirm operational boundary conditions of full-scale operation and removal differential ΔX_i for selected surrogate and operational parameters.	
Step 6	Operational monitoring: Monitor differential ΔX_i of select surrogate and operational parameters for each unit process and/or the overall treatment train on a regular basis (continuously wherever possible).	Verification monitoring: Monitor differential ΔY_i of selected indicator compounds for each unit process and the overall treatment train regularly, but less frequently.

The meaningful use of all of these measures requires that suitable process boundary conditions regarding plant design and operation are maintained. For example, for a reverse osmosis process, both at pilot-scale and full-scale, these boundary conditions might be defined as a source water quality equivalent to UF-treated secondary effluent, pH adjusted to 6.3 to 6.7, addition of scale inhibitors, operation at a recovery of 80 to 85%, and a permeate flux of approximately 20 $Lm^{-2}h^{-1}$.

Suitable chemical indicators of treatment performance were identified prior to the commissioning of the Water Corporation Groundwater Replenishment Trial during 2008 and 2009 (Blair *et al.*, 2010). Existing chemical monitoring data for that scheme were used to determine appropriate chemical indicators of RO treatment performance to be monitored during the trial. The Treatment Performance Indicators were defined using the process described by Drewes *et al.* (2008). These indicators were chosen for their consistent presence in secondary treated wastewater at measurable concentrations, and their chemical character with respect to RO removal. They included large, medium and small organic chemicals as well as a metalloids and anions.

The validity of the indicators to represent removal of other parameters within the group or family was confirmed via a comprehensive set of water quality parameters which were tested and analysed to determine compliance with recycled water quality parameter values.

The treatment performance indicators used during the trial are listed in Table 5. These indicator chemicals were monitored during commissioning validation to confirm their appropriateness as indicators of RO performance and to verify ongoing treatment performance.

Table 5 Treatment performance indicators for Water Corporation Groundwater Replenishment Trial (Blair *et al.*, 2010).

Parameter	Chemical properties represented	Predicted removal based on solute and RO membrane properties[1]	Target minimum removal (%)	Average removal during commissioning (%)
Boron	Small, charged (+ or -), very hydrophilic	Poor rejection	30	26
Nitrate as N	Small, charged (-), very hydrophilic	Moderate rejection	80	90
1,4-Dioxane	Small, uncharged, very hydrophilic	Poor rejection	-	> 80
NDMA	Small, uncharged, very hydrophilic	Poor rejection	30[2]	11
Chloroform	Small, uncharged, slightly hydrophilic	Moderate rejection	30[2]	23
Bromodichloromethane	Small, uncharged, hydrophilic	Moderate rejection	-	20
1,4-Dichlorobenzene	Small, uncharged, hydrophobic	Moderate rejection	50	18
Carbamazepine	Medium, uncharged, slightly hydrophobic	Moderate to high rejection	90	> 93
Diclofenac	Large, charged (-), hydrophobic	Very high rejection	80	> 76
EDTA	Large, charged (+ and -), very hydrophilic	High rejection	90	> 85

1 From Bellona *et al.* (2004)
2 There was formation of these DBPs by chloramination prior to UF, measurement in UF filtrate should improve the confidence in RO performance.

Through the Groundwater Replenishment Trial, it was determined that a number of these potential indicators presented practical difficulties for this scheme. In particular, the disinfection by-products were found to be difficult to interpret due to competing removal and formation processes. As a consequence, this project receded from using treatment performance indicators for regulation, instead focusing on recycled water quality indicators instead. Further investigations are now testing weekly sulphate and pressure vessel conductivity profiling as key RO performance indicators.

Probabilistic characterisation of reverse osmosis treatment performance for a pilot-scale advanced water treatment plant in Sydney, Australia, has also recently been reported (Khan *et al.*, 2009; Khan & McDonald, 2010).

Mixture indicators – bioanalytical tools

Chemicals never occur alone in environmental water and wastewater samples – rather, they occur as complex mixtures. This leads to two significant problems for environmental scientists: a vast list of individual chemicals to analyse, and their potential effects in combination. In some instances, a few well-known chemicals can explain the majority of an observed toxic effect, but they often only explain a small fraction. This is frequently the case with municipal wastewaters after low levels of treatment (Chapman *et al.*, 2011). Also, while the concentrations of individual chemicals can often be below critical levels (such as single-chemical guidelines), the interaction between individual chemicals and the resulting mixture effects may give cause for concern (Escher & Leusch, 2011).

There are no standardised procedures for incorporating potential effects of mixtures – additive, synergistic or suppressive – into the process of setting guideline values for regulatory purposes. Because of inherent uncertainties in the range and concentrations of possible components of complex mixtures in an environmental situation, it is generally not possible to use such information to develop standards.

There are established methods for aggregating estimates of risk when the composition of a chemical mixture is known or can be inferred using relevant data. Such methods usually aggregate risk by assuming that risks are additive, but this assumption implies that chemicals producing the same adverse health outcome act in the same way, which may not be the case. For example, endocrine disruption can operate through different receptors, pathways and signalling webs, and it is difficult to establish whether mixtures of endocrine disrupting chemicals will produce additive effects (with or without synergistic or antagonistic interactions), particularly at the low levels typically associated with environmental exposure.

The Toxic Equivalency Factor (TEF) approach, which is a special case of the concentration addition concept of mixture toxicity, has been proven to be very useful for risk assessment of chemicals with the same mode of toxic action. The International Programme on Chemical Safety of the WHO has been instrumental in developing and supporting harmonised approaches to the risk assessment of mixtures for dioxin-like chemicals, where the TEF approach is applied (Van den Berg *et al.*, 2006). TEFs defined by the WHO working group are internationally accepted and have found their way into many national regulations. They are also a cornerstone of the Stockholm Convention, a global treaty to protect human health from exposure to persistent organic pollutants (United Nations, 2001).

The globally harmonised system for the classification and labelling of chemicals uses a summation method that classifies a mixture in terms of the relative amounts of already classified compounds or on the basis of a similar mixture that is already classified (United Nations, 2003). Only components that exceed 1% of the total concentration need to be included unless there is an indication that a component present at lower concentration is toxicologically relevant.

The use of bioanalytical tools is a rapidly emerging approach that may provide a measure of the overall mixture effect of a water sample (Escher & Leusch, 2011). By using the toxic equivalency concept and by comparing the toxic equivalent concentrations derived from bioassays with the calculated toxic equivalent concentrations from the chemicals identified and quantified by chemical analysis, it is possible to obtain an estimate of the fraction of known and unknown chemicals contributing to toxicity and gain an appreciation of the total toxic potential of the complex mixture.

The standard methods to assess chemical safety of water are based either on epidemiological studies or animal testing (for example, rats and mice). Epidemiological studies are retroactive, and it would be greatly preferable to identify a problem sooner and not wait for a population response. Animal testing is widely used in single chemical risk assessment where exposure doses can be very high, but are of limited relevance for drinking water quality testing because of their relatively poor sensitivity (that is, they are not sensitive enough to detect subtle effects) and high costs (both financial and ethical). However, our understanding of chemically-mediated toxicity has greatly improved over the past decades, and we now know that the initial response of an organism to exposure to chemicals in water is at the molecular and cellular level (Escher & Leusch, 2011).

Measuring toxicity at the cellular level, as is done using bioanalytical tools, therefore provides a valuable tool for hazard assessment. It is important to recognise that not all cellular-level effects will translate into whole-organism toxicity, due to the activity of repair and compensation mechanisms. A cellular trigger is the necessary first step towards observable toxicity in a sequence of events called the adverse outcome pathway. This pathway leads from cellular responses, through organ responses to observable effects at the organism or population level, such as onset of disease. Therefore, the initial interaction of the chemical with its biological target or the direct cellular response to this event provides a sensitive measure of potential toxicity.

While the ultimate goal is protection of human and population health, it is possible to use *in vitro* bioassays as screening tools to quantify the cellular pathways of toxicants. These can be indicators of the hazard potential of chemicals and give information on the relevant modes of toxic action. Thus, bioassay responses are more than just surrogate measures of the presence of micropollutants in a given water sample but can also be used as indicators for groups of chemicals with common modes of toxic action. These indicators are potency-scaled, that is, more toxic chemicals have a greater weighting in a bioanalytical indicator, and unknown chemicals and complex transformation products are accounted for even if they cannot be resolved from other mixture components.

Multiple-barrier systems

The multiple-barrier concept is based on the principle of establishing a series of barriers to preclude the passage of microbial pathogens and harmful chemical constituents into the water system, to reduce risk to appropriate levels. This concept is embedded in Australian water quality guidelines including the *Australian Drinking Water Guidelines* and the Australian Guidelines for Water Recycling. Furthermore, it has been almost universally adopted in all planned potable water recycling schemes internationally.

The Californian Department of Public Health requires that multiple barriers be incorporated in the design and operation of water reclamation facilities that produce recycled water for IPR to augment potable water supplies (CDPH, 2013). Such barriers may include the following (Crook, 2010):

- Source control programs designed to prevent the entrance of constituents of concern into the wastewater collection system that will inhibit treatment or may preclude use of the water. If water and wastewater services are provided by different agencies, a highly functional partnership needs to exist between the two agencies.
- A combination of treatment processes, which may include both conventional and advanced treatment processes, where each process provides a specific level of constituent reduction.
- Constituent monitoring at various points of treatment.
- Design and operational procedures to prevent, rapidly detect, and then correct abnormalities in treatment process performance. Such operational procedures may include real-time monitoring, operator certification, training, stringent operational procedures, monitoring of adherence to such procedures, and redundant systems.
- Environmental buffers that can provide dilution, natural attenuation of contaminants, and retention time.

The advantage of the multiple barrier approach is that the probability that multiple processes will fail simultaneously is small, and the public would be provided a degree of protection even in the event that one of the barriers fails.

Quantitative application and validation of multiple-barriers

The approach taken by the CDPH to pathogenic microorganism control clearly indicates the importance of the multiple-barrier design. Any groundwater replenishment reuse project is required to achieve at least 12-log enteric virus reduction, 10-log *Giardia* cyst reduction, and 10-log *Cryptosporidium* oocyst reduction. In doing so, the treatment train must include at least three separate treatment processes. For each of these pathogens, an individual treatment process may be credited with no more than 6-log reduction, with at least three processes each being credited with no less than 1-log reduction.

A general validation approach for individual treatment processes (for non-potable water recycling projects) has been established by the Victorian Department of Health (Department of Health Victoria, 2013). The requirement for multiple barriers is somewhat similar to that of the CDPH in that a maximum value is applied that can be attributed to any one treatment type, regardless of its capability. In this case, maximum credit is 4-log reduction units for all pathogens. There are a number of justifications given for this approach, including limitations in monitoring capabilities. However, it is emphasised that this is intended to support the adoption of the multiple-barrier approach. The intended outcome is that, for recycled water schemes requiring greater than 4-log pathogen reduction, there are at least two validated treatment process types for the specific pathogen group whereby:

- the predominant mechanisms of pathogen reduction and principles of operation are dissimilar (such as an activated sludge plant, membrane filtration, chlorination and UV disinfection);
- the events that lead to failure differ and are independent (such as an increase in ammonia impacting on chlorination mode versus a ruptured membrane surface);
- operational monitoring techniques are dissimilar, and thereby the limitations and measurement of uncertainty are different (such as turbidity versus free chlorine residual); and
- instrumentation and control loops must be sufficiently independent so that fault or inaccuracy with one control point does not affect another.

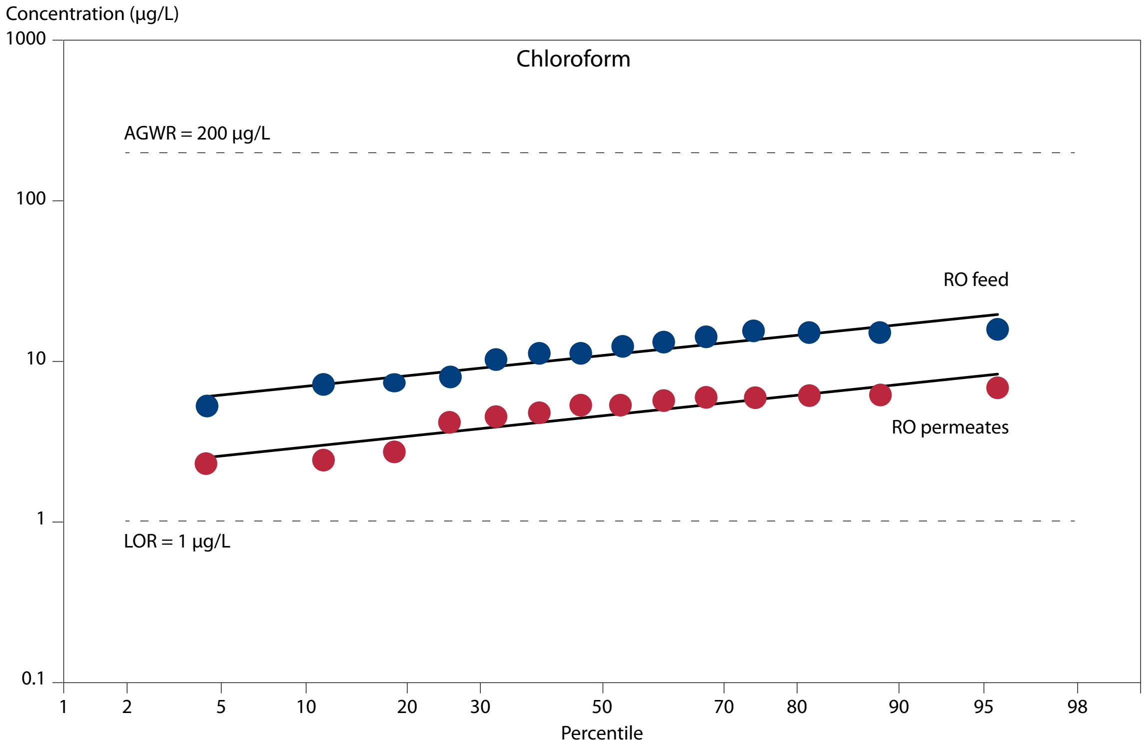
One aspect that is not comprehensively covered in the Victorian guidelines is the evaluation of treatment performance variability. The guidelines state that "the statistical methods used to derive the LRV must be conservative and assigned LRVs must be associated with the conservative end of the uncertainty interval. Typically, this is the fifth percentile or the lower 95% confidence limit of the mean".

Such an approach may be appropriate for a single-barrier system. However, for a multiple-barrier system, the compounding conservative assumptions (5th percentiles) will lead to a validation approval based on a very unlikely (that is, low probability) low value for total system LRV estimation. Determination of a more realistic total LRV estimation would require the avoidance of this compounding of conservative assumptions. This could be achieved by more rigorous evaluation of process treatment performance variability and the combination of LRVs for individual barriers using probabilistic techniques.

The evaluation of treatment variability under normal plant operation may be achieved by summarising observed water quality using basic statistical tools associated with frequency analysis, such as means and standard deviations. The overall system variability may be characterised by estimating the cumulative probability distributions associated with individual contaminants at key treatment units throughout the facility. These probability distributions allow an estimation of the probability that treatment goals would be exceeded. Water quality variability may then be characterised by the construction of lognormal cumulative probability plots.

The process for plotting data in lognormal cumulative probability plots has been described in detail elsewhere (Khan, 2010). As an example, a lognormal probability plot for chloroform concentrations observed after various treatment processes in an AWTP is presented in Figure 13. This plot was prepared by sorting each of the observed measurements from lowest to highest and assigning each as a percentile

Figure 13 Log normal cumulative probability plot for chloroform during RO treatment.



value. Assuming that the sampled data is representative of underlying variability enables the cumulative distribution function (CDF) to be estimated and plotted. This approach gives a clear visualisation of the concentration variability and how that changes over subsequent treatment operations. These plots can also be used to visually bound the data between lower limits of reporting (LOR) and upper treatment targets. A further advantage is that such plots can be prepared even when some of the data is below the LOR since the CDF can be extrapolated from only the available, higher percentile data.

As can be observed from Figure 13, chloroform levels ranged between 5 and 16 µg/L in the RO feed. RO was partially effective in removing chloroform, resulting in a probable combined RO permeate concentration of 2 to 7 µg/L. This chloroform concentration data could then be used to fit full lognormal probability distribution functions (PDFs) such as the example shown in Figure 14. This procedure allows for the estimation of summary statistics such as mean and standard deviation for largely censored data.

Figure 14 Chloroform concentration in RO feed and permeate (µg/L).

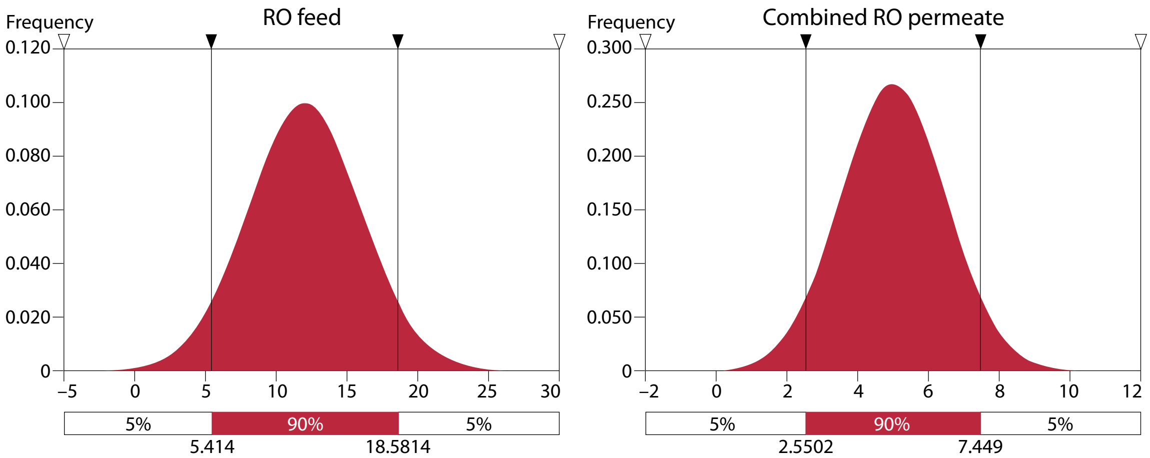
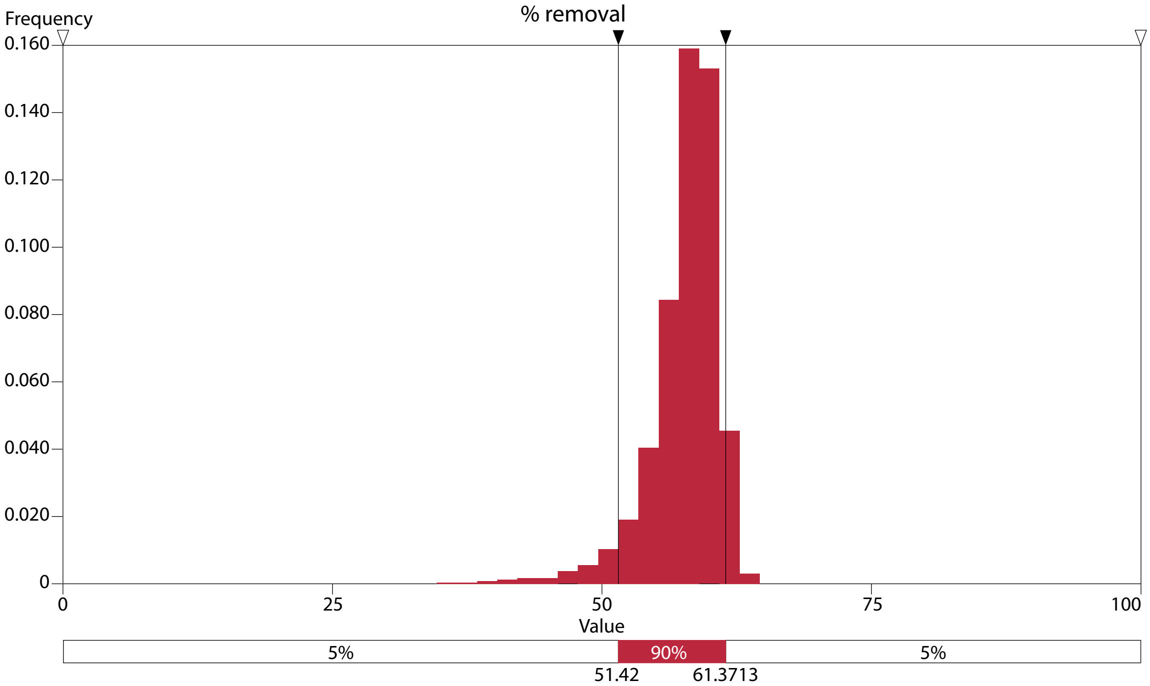


Figure 15 Simulated PDF of chloroform removal (%) from RO feed to RO permeate.



Once PDFs have been fitted to observed chemical concentration data, it is then possible to undertake mathematical manipulations of the PDFs to calculate outcomes such as percentage removal of a particular chemical by a particular treatment process or series of processes. Figure 15 shows the simulated PDF for percentage chloroform removal during RO treatment. This PDF was derived by means of a Monte-Carlo simulation as described by Khan (2010).

In cases where ambient concentrations of suitable indicator compounds are not reliably sufficient to confirm effective removal, challenge testing can be a useful technique for characterising performance.

The objective of challenge testing is to validate the performance of a unit treatment operation for removing trace organic constituents. Typically, the test requires artificially elevating the concentration for the select target compounds in treatment process feed waters to levels sufficiently above the available analytical detection limits. During this time, samples of the elevated feed water and treated effluents are collected. Concentrations in feed and effluent samples are compared to assess the overall level of removal. Examples of challenge testing a reverse osmosis treatment process for chemical contaminants removal have been described (Khan, 2010; Khan & McDonald, 2010).

Probabilistic assessment

Computing sums, multiplications and other transformations on multiple PDFs is a mathematically challenging task that is, in some cases, impossible. For this, probabilistic techniques can provide a powerful alternative approach. Monte Carlo simulation is currently the most widely used method for probabilistic risk assessment (Williams & Paustenbach, 2002; Lester *et al.*, 2007).

Conventional deterministic approaches to water treatment process performance assessment tend to rely on multiple conservative assumptions, which are adopted to compensate for the lack of knowledge regarding uncertainty. When such conservative assumptions are compounded over a multi-step calculation, the effect is often that the calculated risk outcomes are comparable with maximum values resulting from a probabilistic approach. This leads to a risk focus on extreme situations with very low probabilities of occurrence.

Probabilistic assessment relies on the incorporation of numerous stochastic variables to compute a final distributional outcome or prediction. In light of their increasing application, the US EPA has developed guidelines for probabilistic environmental risk assessments (US EPA, 1997). Many of the concepts included in these guidelines could be adapted for DPR process validation.

For many modelled variables, the stochastic nature is derived from two distinct factors: variability and uncertainty. In many cases, it is desirable to separate – as much as possible – the consideration and reporting of these two factors. Such assessments are known as two-dimensional Monte Carlo methods. Not every validation process will warrant a probabilistic assessment. Indeed, six different levels of analytical sophistication in the treatment of uncertainties in risk analysis have been identified by Paté-Cornell (1996). These are summarised as:

- Level 0 – Hazard detection and failure modes identification;
- Level 1 – 'Worst case approach';
- Level 2 – Quasi-worst case and plausible upper bounds;
- Level 3 – Best estimates and central values;
- Level 4 – Probabilistic risk assessment, single risk curve; and
- Level 5 – Probabilistic risk analysis, multiple risk curves.

A useful approach is to undertake a tiered evaluation whereby some aspects are deemed to be within acceptably safe limits without the need for intensive scrutiny (Paté-Cornell, 1996). Further efforts and resources may then be allocated only to those aspects that require such additional efforts in order to establish that acceptable performance may be met, or to demonstrate that further controls are needed.

The first tier of a tiered treatment validation would normally consist of a very conservative validation requiring minimal data. Variables that might otherwise be considered stochastically are assigned conservative point-values on the basis of worst-case assumptions. Examples include zero membrane rejection of a chemical during treatment by a membrane bioreactor. Treatment performance shown to be validated to an acceptable level under 'tier 1 conditions' would require no further evaluation. Processes that are not validated to an acceptable level under tier 1 conditions are then further subjected to a second tier assessment, which can require significantly more data and more complex analysis. A probabilistic analysis may be helpful in such circumstances since this involves carrying full PDFs through multiple calculations, thus avoiding the need for compounding conservative assumptions.

Probabilistic models may be constructed from most deterministic risk calculations simply by replacing single-value variables with PDFs. The existing mathematical transformations, such as multiplications or additions, will still apply.

Validation of full treatment process trains, i.e. multiple barriers, may be determined in terms of sequential treatment processes, each with variable capability to reduce the concentration of a specific chemical or pathogen. A probability density function can be used to describe the variability in source water concentration of the chemical. Subsequent PDFs then describe the variable percentage or fractional removal of the chemical by various treatment processes such as reverse osmosis and advanced oxidation. These PDFs can then be used to derive a simulated PDF for final effluent concentration.

The approach of assessing sequential unit water treatment operations and combining the PDFs by probabilistic techniques was used very effectively in the assessment of a pilot-scale AWTP in San Diego (Olivieri *et al.*, 1999). In that study, PDFs were generated for plant influent water quality and sequential treatment performance of four types of treatment processes (microfiltration, ultrafiltration, reverse osmosis, and chlorine disinfection). These PDFs were generated by a combination of challenge tests and theoretical considerations. A key advantage of this process was that it allowed for the mathematical estimation of the entire treatment train performance. This estimation would not have been possible simply by end-point sampling since final effluents consistently yielded results below detection thresholds.

System reliability

Considering the quality of the source, any potable reuse scheme needs to be designed to reliably supply a finished water quality that is safe for human consumption at all times. System reliability of a reuse project is defined as the probability of adequate performance for a specified period of time under predefined conditions. Several factors affect the engineered system reliability (Asano *et al.*, 2007):

- variability of wastewater characteristics;
- inherent variability of biological treatment processes;
- inherent variability of advanced water treatment processes;
- reliability of mechanical plant components; and
- effectiveness of monitoring.

System reliability requirements may include standby power supplies, equipment replacement and preventative maintenance schedules, readily available replacement equipment, online monitoring of system performance and water quality, redundant process components critical for the protection of public health, flexible piping and pumping configurations, and emergency storage or disposal options.

Whether a particular reuse system is able to reliably produce and deliver drinking water that meets health targets can be evaluated through risk assessment. Thus, potable reuse projects must include an evaluation of the potential health risks and hazards that could compromise the reliable delivery of safe drinking water that is derived from reclaimed water.

Operator reliability

In addition to engineered system reliability, operator capability and performance, including the potential for 'human error', is an important determinant of overall system reliability. In fact, the majority of identified waterborne disease outbreaks in developed countries have involved some degree of human error as a causative factor (Hrudey & Hrudey, 2004). The Australian Guidelines for Water Recycling state that a number of key principles are fundamental to safe augmentation of drinking water supplies. (NRMMC, EPHC & NHMRC 2008). The need for appropriate skills and training for designers, operators and managers of water recycling schemes is highlighted among these key principles.

Various factors can assist to ensure that these requirements are met. All persons involved in the design, management, operation and audit of recycled water systems must have sufficient and appropriate knowledge and skills for their roles. They must also be aware of the consequences of failure or poor performance. Responsibilities and accountabilities must be identified, communicated, understood and supervised.

Organisations and contractors responsible for drinking water augmentation schemes must ensure that operators have sufficient and appropriate training and qualifications to undertake their tasks. Where available, accredited training and certification programs should be mandatory. Overall operation of the treatment process must be supervised by managers with appropriate expertise in engineering and quality assurance.

In order to ensure the operational reliability of DPR projects, it will be necessary to foster high levels of expertise and personnel training within the Australian water industry. This must be supported by mechanisms to ensure compliance with requirements to only use appropriately skilled operators and managers. These initiatives will be essential for any future DPR implementation and are also essential to maintain high levels of safety with current water supply systems.

Epidemiologic studies

Epidemiologic studies examine the health statistics of a population in order to try to identify causes of illness. Significant epidemiologic studies have been conducted for two major international potable water recycling schemes. These are the DPR scheme at Windhoek (Namibia) and the major IPR scheme in Montebello Forebay, California (USA).

The Windhoek scheme is situated within a very different social and public health context compared to Australia. Accordingly, the transferability of public health studies and epidemiologic outcomes to Australia is questionable. For this reason, the various studies conducted in Windhoek are not reviewed here. However, interested readers are directed to publications by Sayed *et al.* (1989), Hattingh & Bourne (1989), Odendaal (1991) and Hrudey & Hrudey (1990) for more information.

At least three epidemiologic studies have been conducted to examine health risks associated with the Montebello Forebay Groundwater Replenishment Project. The first studied health outcomes from 1969 to 1980 (Frerichs *et al.*, 1982; Frerichs, 1984). The second examined cancer incidence, mortality and infectious disease outcomes from 1987 to 1991 (Sloss *et al.*, 1996). The third evaluated the incidence of selected adverse birth outcomes between 1982 and 1993 (Sloss *et al.*, 1999).

Importantly, no infectious disease problems associated with any of these schemes, (or other less studied schemes, have been detected. However, such epidemiologic studies have the following limitations in terms of pathogenic organisms:

- all epidemiologic studies are relatively insensitive as a means of detecting impact because background levels of gastrointestinal illness from other sources such as food contamination tend to obscure any 'signal' from water;
- sensitivity in detecting disease is poor in comparison to conservative targets such as 10^{-6} DALYs and 10^{-4} infection risk per year; and
- the studies undertaken in the US relate to IPR by aquifer recharge and aquifer characteristics tend to be relatively location specific.

The main benefits of epidemiologic studies are: the confirmation that there is no substantial problem; public reassurance; and the potential detection of outbreaks or other impacts on exposed populations.

Chapter 8 Cost implications, energy consumption and greenhouse gas emissions

Many towns and cities around the world are addressing their future water security needs and have a wide range of options to evaluate, ranging from the expansion of existing raw water storages, non-potable reuse applications for both domestic and industrial uses, potable reuse, and seawater desalination. There are now many examples – as shown in Chapter 2 – of IPR and, more recently, DPR being selected after exhaustive analysis.

Among the potential attractive features of DPR are assumed to be reduced capital and operational costs compared to IPR. However, there is a diverse range of factors that should be considered when attempting to make this comparison. The key factors leading to possible cost differentials between DPR and IPR are described below.

Possible sources of cost savings for DPR

A number of possible sources of cost savings for DPR compared to IPR can be conceived of, depending on scheme characteristics. Most of these were identified in the qualitative stakeholder survey as described in Chapter 5. A number of them were identified as important considerations in some of the existing and planned DPR schemes described in Chapter 4. Chapter 8 and Appendix B also address the potential savings attributable to DPR and address broader sustainability considerations.

Construction and maintenance of transfer systems to a suitable environmental buffer

Most IPR schemes, particularly those that rely on large surface water environmental buffers, tend to rely on extensive enclosed pipelines and associated pump stations to deliver water from the AWTP to the environmental buffer. By transferring water shorter distances to drinking water treatment plants, or direct to distribution systems, some DPR schemes may present considerable savings in the need for transfer systems – as shown in the hypothetical case study summarised here and presented in Appendix B.

Pumping costs to transfer water to a suitable environmental buffer

In addition to the costs associated with constructing water transfer systems, DPR systems may offer proportional cost saving in the operation of these systems. Pumping water long distances, especially to higher elevations, and extraction of groundwater, are notoriously expensive. These costs can be expected to increase as the price of energy rises.

Assessment of the suitability of an environmental buffer to receive reclaimed water

IPR schemes that require the services of an environmental buffer will generally require environmental assessment and approval for the role of the 'discharge' or treated reclaimed water. This applies to both groundwater and surface water buffers. It may include environmental assessment such as potential impacts to aquatic species and habitats. It may also include assessment of potential public health impacts to recreational and consumptive users of water from the environmental system. By avoiding the use of environmental buffers, DPR systems may avoid such environmental assessments and hence, the costs associated with them.

Assessment of the performance of an environmental buffer for water quality improvement objectives

Some IPR schemes may be designed and assessed in such a way that the environmental buffer is assumed to provide a quantifiable water quality benefit. In such cases, there may be a requirement to assess or validate this benefit. The Australian regulatory system in particular tends to require comprehensive validation of any processes to be credited as contributing to final water quality as a barrier for trace chemicals or pathogenic microorganisms, and in many cases does not view the environmental buffer as a 'treatment barrier' in terms of process validation.

Re-treatment of water that has been highly purified then released to the environment

Many IPR schemes involve the treatment of water to exceptionally high qualities by processes including reverse osmosis and advanced oxidation. This highly treated water is then returned to an environmental buffer where it mixes with other environmentally sourced water and is prone to environmental contamination. In such cases, important water quality parameters, such as total organic carbon and total dissolved solids, may be affected. This can impact the requirements and costs of subsequently re-treating this water by conventional treatment processes. In some cases, this detrimental impact to the cost of re-treating the highly treated reclaimed water may be off-set by positive impacts for treatment of the blended water compared to the purely environmentally sourced water.

Possible sources of additional costs for DPR

In addition to potential cost savings, DPR schemes can be expected to incur additional costs, compared to IPR, for some aspects of their overall operation. Similar to potential savings, these are likely to be relatively case-specific and may also be significantly influenced by local factors, including regulatory requirements.

Additional engineered treatment processes

In some cases, in order to achieve water quality requirements and satisfactory risk profiles, DPR schemes may require additional engineered treatment processes compared to IPR schemes. While this is a possible source of additional cost, there appears to be little evidence that such additional treatment processes have been required for schemes approved in the US and South Africa.

Additional water quality or process performance monitoring

Significant expectations for water quality monitoring and process performance monitoring would certainly be placed on any Australian DPR project. Previous experience with IPR projects (for example, the Western Corridor Water Recycling Project) has shown that these monitoring requirements may comprise a significant component of overall operational costs for some potable reuse schemes. Potentially tighter turn-around times for some measurements, due to reduced detention times, may further exacerbate some monitoring costs.

Engineered storage buffers

The construction and maintenance of engineered storage buffers would impose an additional cost to a DPR project, not faced by a comparable IPR project. It is notable that many of the existing DPR schemes have not required major engineered storage capacity, but regulatory requirements may determine the need in future cases.

Management of public acceptance

Public acceptance was among the most commonly identified obstacles to the development of DPR in the qualitative stakeholder survey (Chapter 5). As such, it appears that significant up-front and on-going investments may be required to manage potentially negative public perceptions of DPR in Australia. Costs may include the employment of dedicated public relations managers and the production of well-prepared community information materials.

Readers are referred to the Australian Water Recycling Centre of Excellence's (AWRCE's) *National Demonstration, Education and Engagement Program* (NDEEP) that is currently being developed as part of its Goal 3 research project; "Reclaimed water is viewed as an acceptable 'alternate water' for augmenting drinking water supplies".

Staff training

Treatment plant operator competency and other advanced personnel skills such as risk assessment and risk management were also identified as significant issues in the qualitative stakeholder survey (Chapter 5). Additional ongoing training costs will likely be required in order to maintain satisfactory competency levels.

Water production performance and operational reliability, both mechanical and human operators, are addressed in the AWRCE's NDEEP research initiative.

Energy consumption and associated greenhouse gas emissions

By their nature, IPR schemes require that treated reclaimed water is transported back to a significant surface water catchment or groundwater aquifer. In many cases, this may involve pumping water long distances and to higher elevations. A potential advantage of DPR is the avoidance of some of this pumping if shorter distances and lower elevation can be achieved to return the water direct to the distribution system.

Two examples of this 'potential advantage' in Australia would be:

- the Western Corridor Water Recycling Project in South-East Queensland is an IPR scheme in which the water is intended to be pumped to a release point in Lake Wivenhoe, rather than either to the Mt Crosby water treatment plant, located some 40 km closer than the currently intended release point, or directly into the drinking water distribution system; and
- Sydney Water's study in 2005 comparing IPR with seawater desalination. This scenario considered a hypothetical IPR scheme that involved the transfer of recycled water from Malabar Sewage Treatment Plant to Sydney's primary raw water supply, Lake Burragorang (Warragamba Dam). An alternative DPR scenario of pumping the water either only as far as the Prospect Water Filtration Plant or, indeed, into a service reservoir nearer to the city, was not considered, but would have involved a significantly shorter distance and much reduced pumping elevation.

In addition to the expense associated with constructing such pipelines, the energy associated with pumping water over such long distances presents significant additional operational costs and greenhouse gas emissions implications compared to schemes that require less pumping.

Most Australian states rely heavily on the combustion of fossil fuels such as coal and natural gas for electricity production. As such, energy consumption from local electricity grids is closely associated with greenhouse gas emissions, primarily as carbon dioxide (CO_2) produced from hydrocarbon combustion. In contemporary greenhouse gas accounting systems, these emissions from purchased electricity are categorised as 'Scope 2' emissions and are quantified as kilograms of CO_2-equivalents. The precise number of CO_2-equivalents assumed to be produced per kilowatt-hours of purchased electricity is provided by the Commonwealth Government as shown in Table 6 (Australian Government IICCSSRTE, 2013). Figures vary between states as a consequence of variable combinations of fuel sources, as well as power production and distribution efficiency.

Table 6 Scope 2 emissions for electricity purchased from a grid (Australian Government IICCSSRTE, 2013).

Sate, Territory or grid description	Emission factor kg CO_2-e/kWh
New South Wales and Australian Capital Territory	0.87
Victoria	1.17
Queensland	0.82
South Australia	0.62
South West Interconnected System in Western Australia	0.78
Tasmania	0.20
Northern Territory	0.69

Additional greenhouse gas emissions can be attributed to other indirect sources, including the extraction and production of purchased materials, electricity-related activities (for example, transmission and distribution losses) not covered in Scope 2, and outsourced activities such as waste disposal. These types of additional emissions are categorised as Scope 3 emissions (Australian Government IICCSSRTE, 2013).

Actual energy efficiency benefits and associated savings in greenhouse gas emissions will be highly dependent on the specific characteristics of any DPR scheme relative to any other scheme to which it may be compared. As such, it is not possible to provide precise figures in any general sense.

Hypothetical scenario comparative case study

Many of the respondents to the qualitative survey in Chapter 5 presumed that DPR could achieve significant energy and/or cost savings compared to IPR. In order to test these presumptions, a lifecycle-based engineering assessment was commissioned (GHD, 2013). The full assessment is included as Appendix B of this report and is available online at www.atse.org.au/water-reports.

This assessment was intended to provide an indication of the potential sources and scope of energy and cost savings that may apply to some DPR projects compared to alternative water supply options. As such, all assumptions and conclusions are purely hypothetical. While indicative findings are presented in this Chapter, interested readers are encouraged to refer to Appendix B for full details. It should be noted that energy requirements and costs associated with the various types of water supply options assessed here are known, in practice, to be highly case-specific.

Four hypothetical options were defined for alternative water supply to an urban city at a coastal location in Australia as described below. The nominal total capacity of treatment and delivery systems for all options was an average of 120 ML/d of product water or at least 40 GL/year. Further details regarding assumed capacity, sizing and treatment are provided in Appendix B.

OPTION 1

Seawater desalination (SWRO) – producing product water that is fed into an assumed pre-existing potable water distribution system of the hypothetical city.

OPTION 2

Indirect potable reuse (IPR) – advanced water treatment, followed by recycling via a regional impoundment (for example, dam) that serves as raw water source for conventional potable supply to the hypothetical city. The impoundment with its catchment and conventional potable water supply, treatment and distribution system were all assumed to be pre-existing. Water recycling supplements raw water supply in this scenario.

OPTION 3

Direct potable reuse (DPR) – advanced water treatment, followed by recycling via a local reservoir that forms part of the conventional potable supply distribution system to the hypothetical city. The conventional potable water source, supply, treatment and distribution system were all assumed to be pre-existing. Water recycling supplements potable water supply in this scenario.

OPTION 4

Dual pipe reuse – advanced treatment of secondary effluent from a modern wastewater treatment plant, producing recycled water of suitable quality for non-potable uses (for example, toilet flushing and outdoor uses such as washing of exterior surfaces, irrigation of gardens, parks and golf courses, and fire-fighting). A key difference for this option, compared with the other options considered, is that the reclaimed water reticulation network (the 'dual pipe system' for urban water supply) was assumed to be new, i.e. not pre-existing. That is, it was assumed that the 'dual pipe' system would have to be built, most likely as part of a new urban development, as a requirement for this option.

A simplified diagrammatic representation of the hydraulic grade line for the four options is given in Figure 16. Process flow diagrams for the four options are given in Appendix B.

Flow-specific power consumption for the four options is presented in Figure 17. Option 1, SWRO, was determined to have the highest electricity, or power, consumption. Power consumption was dominated by that required for water production, which in turn is largely due to the higher osmotic pressure, and hence higher pressure required for reverse osmosis, of seawater compared to the other options. The water recycling options (Options 2, 3 and 4) take feed in the form of treated wastewater at lower osmotic pressures, and hence require less energy for treatment.

The increased power required for product water delivery in Option 2, IPR, was due to the longer pipeline and higher discharge elevation for this option. However, despite this increase, Option 1 retained a higher power consumption on a flow-specific basis than Option 2. It was concluded that Option 2 would approach Option 1 in terms of power consumption on this basis if the product delivery pipeline was significantly longer than 100 km.

Option 3, DPR, was determined to have a lower flow-specific power requirement, as expected, given the shorter pumping distance for product delivery.

Figure 16 Simplified diagrammatic representation of the hydraulic grade line for the four options.

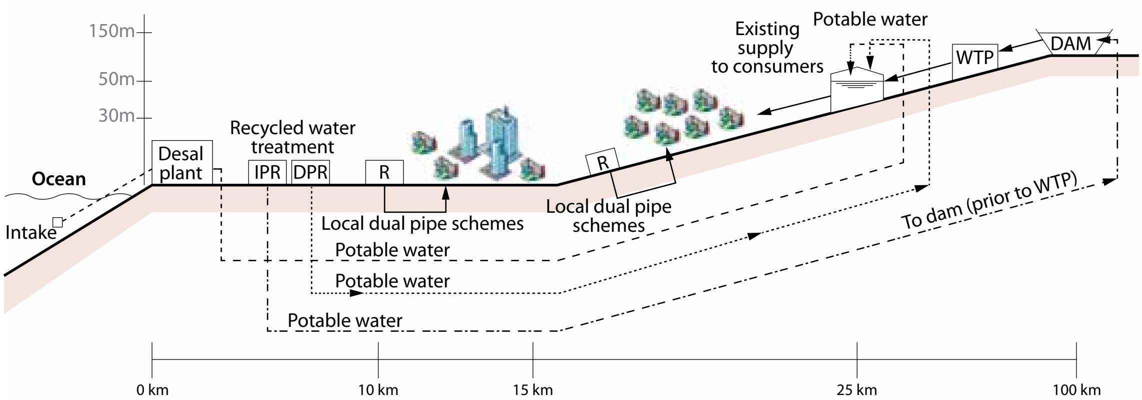


Figure 17 Flow-specific power use, with breakdown, for the options considered (Appendix B).

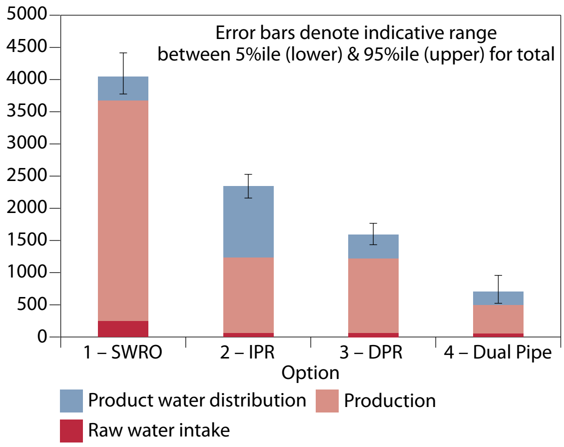
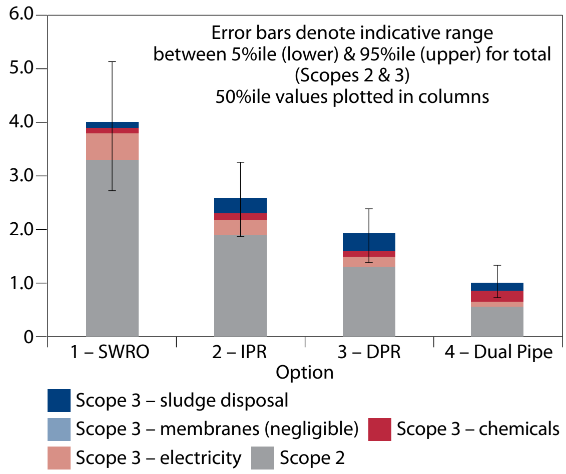


Figure 18 Flow-specific greenhouse gas estimates, with breakdown, for the options considered (Appendix B).



Option 4, dual pipe, had the lowest flow-specific power requirement of the options considered, mainly due to the absence of reverse osmosis and shorter pumping distances with lower elevations assumed for product delivery in the local areas connected to the dual pipe recycled water network.

Comparison of the options on a flow-specific basis for greenhouse gas (GHG) emissions, with a breakdown between Scopes 2 and 3, is given in Figure 18. This assessment shows that the GHG emission profiles were dominated by electricity purchased from the grid, which is the sole contributor to Scope 2. Scope 3 emissions make a bigger relative contribution for the options with the lower overall power requirement. For example, for Option 4, Scope 3 contributions were 43% of the total GHG emissions. At the other extreme, for Option 1, Scope 3 contributed only 17% of the total emissions on the same basis.

Like energy requirements, cost impacts for a DPR project compared to an IPR project can be expected to be highly case-specific and therefore difficult to generalise, other than to say that the water transfer costs can be expected to be lower.

The hypothetical comparative case study presented in Appendix B addresses the costs of the same four hypothetical scenarios discussed here, and a summary of the calculated indicative capital costs (CAPEX), operating costs (OPEX), and net present value (NPV) of the four options is presented in Table 7.

Table 7 Summary of indicative capital costs, operating costs and net present value for hypothetical options considered.

	Option 1 – seawater desalination	Option 2 – indirect potable reuse	Option 3 – direct potable reuse	Option 4 – dual pipe reuse
Plant CAPEX	\$729 M	\$387 M	\$387 M	\$289 M
Transfer & reticulation CAPEX	\$230 M	\$900 M	\$230 M	\$920 M
Total CAPEX	\$959 M	\$1287 M	\$616 M	\$1209 M
OPEX	\$89 M/yr	\$72 M/yr	\$53 M/yr	\$18 M/yr
NPV[1]	\$2128 M	\$2199 M	\$1316 M	\$1386 M

1 NPV assumes 6% discount rate over 30 years, with all CAPEX occurring in Year 1

The indicative project capital cost breakdown for four options is presented in Figure 19. The treatment plant only indicative capital cost breakdowns are provided in Figure 20.

Figure 19 Indicative project capital cost breakdown for four options considered (Appendix B).

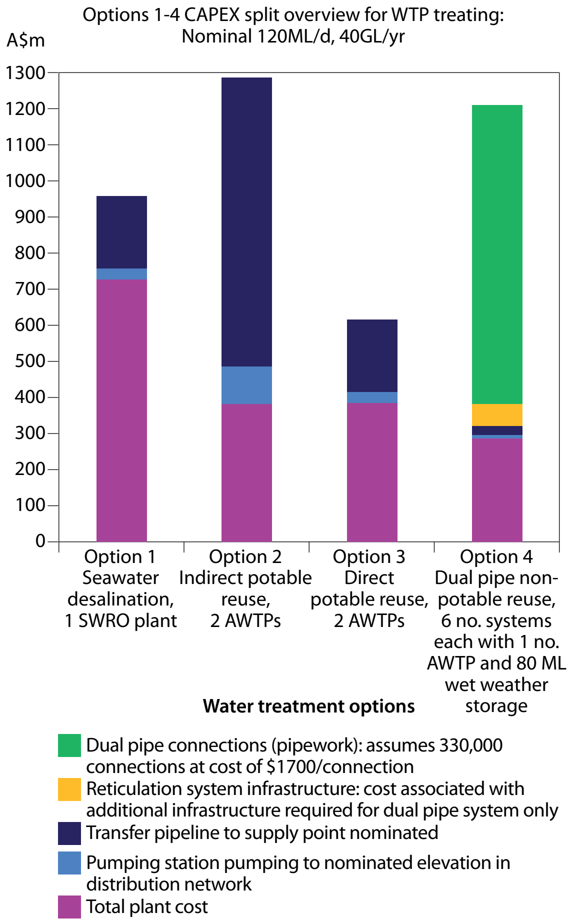
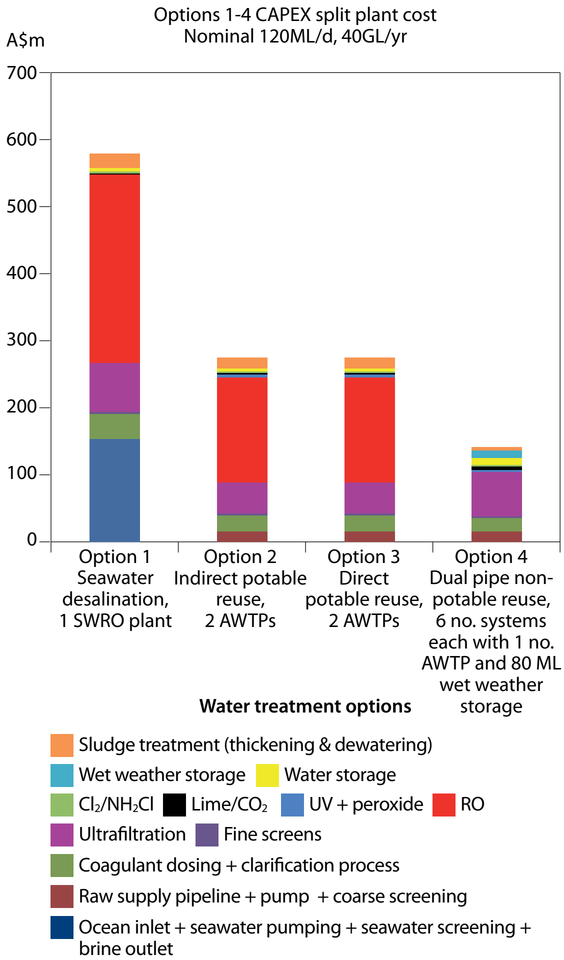


Figure 20 Treatment plant only indicative capital cost breakdown for four options considered (Appendix B).



The desalination plant CAPEX was determined to be relatively high compared to the other options, but given desalination plants are located in close proximity to the sea, a shorter transfer pipeline and lower head was required, resulting in considerably lower transfer system costs as compared to some of the other options. This emphasises a key point in comparing different options. Pipelines are expensive to build and also increase operating costs through energy use. Therefore, the location of treatment facilities and the networks that they connect to are significant, possibly even overriding, factors in cost comparisons. Hence, to some extent, this will always be a location-specific consideration.

Due to the longer distance specified to transfer recycled water from the point of wastewater collection and treatment to dams as source of potable water, and the requirement to construct such a pipeline through urban and rural areas, the IPR option had a high transfer system cost which dominated the cost factors for this option. Given WWTPs are located at low elevation and dams at higher elevations for gravity supply, this factor is likely to affect the cost competitiveness of an IPR option compared to alternative options.

For this assessment, the capital cost for dual pipe reuse was determined to be roughly equivalent to the IPR option. Given the shorter connection to supply recycled water directly to the transfer pipeline for the DPR option, and given essentially the same process treatment train as for the IPR option, DPR had a lower capital cost. In fact some comparison between the graphs shows that considerable additional treatment could be applied to the DPR option before the cost penalty for the longer pipeline length of the IPR option is exceeded.

To be able to realistically compare dual pipe recycled water plants to the other alternative options presented, it was necessary to assume multiple smaller plants were located in close proximity to WWTPs. Total Plant Costs were therefore higher due to the loss of economies of scale, but transfer costs were reduced due to the shorter distance to the point of supply. However, the dual pipe reticulation systems added significant capital cost for this option, compared with the DPR option, where the potable water reticulation network was assumed to be pre-existing.

Finally, on a whole-of-life cost basis, i.e. NPV, given the assumptions underlying the options defined for this investigation, Options 1 and 2 (SWRO and IPR) are comparable and have the highest NPV. Options 3 and 4 (DPR and dual pipe recycled water) have lower and comparable NPV. There is a trade-off for all options between feed transfer and treatment plant costs on the one hand, and product water transfer, or reticulation system, costs on the other hand.

Chapter 9 Social acceptance of DPR

Among the strongest and most consistent messages from the qualitative survey, described in Chapter 5, was that the successful implementation of any DPR project in Australia would depend heavily on public perception and acceptance. Indeed, during the past two decades there have been a number of IPR schemes proposed in Australia which have not eventuated, owing to strident community opposition. These unsuccessful proposals have generally been in South-East Queensland with the cities of Caloundra/Maroochy (planning during 1995–98), Caboolture (1996–97) and Toowoomba (2005–06) being the most prominent examples.

Nonetheless, research has shown that knowledge of and information about water augmentation strategies can increase public acceptance (Dolnicar & Hurlimann, 2009). There is much academic literature to consider on the factors that influence the levels of acceptance of potable reuse schemes in general. Relatively little attention has been paid specifically to issues of DPR compared to IPR, but it may be anticipated that many of the issues will be at least as, if not more, significant for DPR (Nellor & Millan, 2010).

Factors that influence community attitudes to water recycling

Since the 1970s, numerous studies have been undertaken to characterise community attitudes to potable and non-potable water recycling in various countries, including Australia (Po *et al.*, 2004). These have generally indicated strong and widespread support for the recycling of wastewater to irrigate recreational parks, golf courses, lawns, gardens and hay pastures. Substantial acceptance has also been reported for the irrigation of dairy pastures and edible crops including orchard, vineyard and vegetable crops. However, community support for water recycling projects has been reported to wane as the intended uses of the water increased the degree and likelihood of close personal contact. For example, while some household uses such as toilet flushing and clothes washing had high rates of acceptance, uses with closer contact such as swimming and bathing had only moderate support. The lowest levels of acceptance were consistently reported for ingestive uses such as drinking and cooking.

While the likely degree of close human contact is clearly important in determining community acceptance of water recycling schemes, many of the studies have involved theoretical proposals and 'in principle' support. Where actual or potentially imminent water recycling projects are involved, factors such as environmental and conservation matters as well as water treatment and distribution costs tend to be more important (Bruvold, 1988). Accordingly, reported widespread 'in principle' acceptance does not automatically translate into acceptance for real projects. On reviewing available literature, researchers at the CSIRO identified a number of factors that may influence the behavioural acceptability of a recycling scheme to the general community, including (Po *et al.*, 2004):

- disgust or the 'yuck factor';
- perceptions of risk associated with using recycled water;
- the specific uses of recycled water;
- the sources of water to be recycled;
- the issue of choice;
- trust and knowledge;
- attitudes toward the environment;
- environmental justice issues;
- the cost of recycled water; and
- socio-demographic factors.

A further review of past studies has identified principal factors contributing to the degree to which the community will accept potable or non-potable water recycling proposals (Hartley, 2003). It concluded that community acceptance of water recycling is higher when:

- the degree of human contact is minimal;
- protection of public health is clear;
- protection of the environment is a clear benefit of the recycling;
- promotion of water conservation is a clear benefit of recycling;
- cost of treatment and distribution technologies and systems is reasonable;
- perception of wastewater as the source of recycled water is minimal;
- awareness of water supply problems in the community is high;
- the role of water recycling in the overall water supply scheme is clear;
- perception of the quality of recycled water is high; and
- confidence in local management of public utilities and technologies is high.

To fully understand community attitudes to water recycling, it is necessary to consider instinctive and emotional responses that people have to human excrement and sewage issues. It has been illustrated that many people trust their own impressions of water quality, which are often based on cloudiness of the water, more than they trust medical and scientific evidence (Hartley, 2003). Cognitive factors such as the Law of Contagion and the Law of Similarity may explain many of the less rational perceptions that people may have about water recycling (Haddad, 2004). The Law of Contagion suggests that once water has been in contact with contaminants it can be psychologically very difficult for people to accept that it has been purified. The Law of Similarity suggests that the 'appearance' of a substance's condition or status is psychologically linked to perceptions of reality. Combined, these factors can create mental barriers to the acceptance of recycling water for drinking.

The credibility of the water recycling organisation and its senior managers will impact significantly on stakeholder perception of any proposed scheme. An Australian study reported that the degree of trust that an individual held for a water authority was proportionate to the individual's level of confidence that a planned reticulated recycled water supply would not pose unacceptable risks to their health or garden (Hurlimann & McKay, 2004). The credibility of a water recycling organisation will be judged on a number of factors, which may include perceptions of their:

- commitment to the welfare of stakeholders;
- performance record based on previous initiatives;
- knowledge of the issues, as demonstrated by spokespersons; and
- impartiality regarding the subject matter.

In instances where the community associates a high level of risk with a water recycling project, trust has shown to be maximised when the following conditions are met (Renn *et al.*, 1995; Hartley, 2003):

- dialogue is sustained;
- the community has independent sources of information, not linked to the sponsoring agency;
- the community can ask questions;
- the community is involved early;
- information is available to everyone;
- behaviour is non-coercive; it is considered a rational and fair way to make a decision;
- everyone's opinion matters and there is a willingness to listen to all views and expand the discussion if necessary; and
- citizens have some level of control in the process, such as by contributing to the agenda or ground rules.

Religion

During a stakeholder survey undertaken in South Africa, some stakeholders commented that some members of the public might object to DPR on religious grounds. However, subsequent research undertaken in eThekwini failed to find any fundamental religious or faith based objections to potable reuse (Wilson & Pfaff, 2008). In relation to Islam, the authors of that study cited Faruqui *et al.* (2001), noting that a Saudi fatwa on the acceptability of treated wastewater for drinking could provide guidance to other Islamic groups:

> *Reusing wastewater is not haraam, provided that it will not cause harm. After a detailed study, in consultation with scientists and engineers, the Council of Leading Islamic Scholars (CLIS) in Saudi Arabia concluded in a special fatwa in 1978 that treated wastewater can theoretically be used even for wudu and drinking, provided that it presents no health risk.*

Wilson and Pfaff (2008) also found that, while health risks from polluted water were a concern to members of the Hindu Temple, the perceived positive environmental outcomes could be a significant countervailing factor. Members of the Buddhist community were also influenced by the potential for positive environmental outcomes. Spiritual concern over beneficial environmental outcomes may be relevant to DPR projects, which can have both positive (for example, avoiding 'contaminating' environmental buffers and the surrounding landscape), and negative environmental impacts (for example, diverting water from environmental flows and disposal of treatment wastes).

Challenges for direct potable reuse

It should be remembered that many proponents of IPR consider the incorporation of some form of environmental buffer to be a necessary factor for achieving public confidence and support. The responses collected in the stakeholder survey for this project provide ample evidence for this. As such, it may be assumed that DPR will face more significant challenges, and perhaps more intense opposition, than IPR. Indeed, one might expect the 'yuck factor' to be of greater intensity for DPR, since direct connection between wastewater as a source of drinking water is more profound.

The stakeholder survey also reveals that many people consider the environmental buffer to play an essential, and perhaps irreplaceable, role in providing a degree of water quality safety. Formal research on this topic is scant, but it appears to be an important reason why some people maintain a preference for IPR over DPR.

A much less common, but somewhat compelling, point of view expressed in the stakeholder survey was that the apparent requirement for an environmental buffer undermined the message that advanced treatment processes could reliably provide safe drinking water.

Unfavourable public perceptions of DPR, and water recycling more generally, are assumed to be among the main challenges for DPR. Previously, a common explanation for the public's rejection of water recycling has been the 'deficit' in the public's knowledge about the science and technology behind water recycling (Stenekes *et al.*, 2006). The solution to the public acceptance problem was seen simply in terms of better public education. It has been demonstrated that some opponents to water recycling have adopted their point of view based on inadequate or erroneous information (Russell & Lux, 2009). However there is increasing recognition of the need for a range of communication strategies across different media but, importantly, using uniform and precise terminology and imagery in order to go beyond information provision to build greater trust and confidence (Nellor & Millan, 2010).

Nellor and Millan (2010) identified the following challenges for progress in DPR:

- a lack of consensus in the water recycling industry about the worthiness of DPR;
- regulations that mandate recycled water pipes and fittings to be clearly marked as 'purple pipes' and not fit for drinking;
- previous statements by national research bodies that labelled potable reuse as an option of last resort;
- a lack of consensus in the scientific community about the safety of potable reuse, including 'constituents of emerging concern' such as pharmaceuticals, personal care products and endocrine-disrupting chemicals;
- a lack of faith in government agencies' capacity to safely operate and monitor potable reuse projects, and in particular a lack of confidence that the government would promptly inform the public of any safety incidents; and
- a lack of faith in the failure controls of treatment systems.

In response to these identified challenges, participants at a Direct Potable Reuse Workshop held in Sacramento, California, identified five priorities for improving public acceptance of DPR (California Urban Water Agencies *et al.*, 2010):

- Develop appropriate terminology that is easy to understand and consistent with regulations to instil credibility and confidence
- Survey stakeholders to: determine the extent to which the public differentiates between DPR and IPR; evaluate public perceptions of the definition and need for environmental buffers; identify how opposition to DPR may be different to opposition to IPR; and determine why proponents support DPR
- Develop consistent terminology and strategic messages that address safety and quality concerns and, in particular, the measures that compensate for the 'loss' of the environmental buffer, such as real or perceived treatment and 'time-safety' benefits
- Develop a communications strategy that is proactive: that starts before any specific DPR project has been proposed; considers alternative project designs; incorporates learning from prior water recycling projects; understands human nature towards water and uncertainty; provides useful information that facilitates self-education about DPR and the water cycle; aims to develop trustworthiness by consistent, transparent communication with the public, community leaders, and the media; uses a 'hands-on' approach to better engage with the public; and listen to and work with opponents of DPR.
- Implement a communications strategy.

The last two issues identified by Nellor and Millan (2010) incorporate a significant technical issue. That is, the need to establish appropriate operational controls that will enable timely intervention and responses to prevent supply of non-compliant water. Existence of these measures will likely provide an important component of communication with the public about the safety of DPR.

Using context and language to shift attitudes to DPR

Language

Research indicates that specific words used to communicate water recycling messages, both positive and negative, have a strong influence on public perceptions. Different language may be necessary to deliver targeted messages because different stakeholder groups tend to frame water recycling issues differently (Stenekes *et al.*, 2006). However, it has been argued that the terminology currently used to communicate water recycling messages has been inconsistent, confusing, and difficult for the general public to understand or, worse, may have unnecessarily alarmed the public (Marks & Zadoroznyj, 2005; Tsagarakis *et al.*, 2007; Simpson & Stratton, 2011). Menegaki *et al.* (2009) found that the use of 'recycled water' instead of 'treated wastewater' increased end users' willingness to use the water because treated wastewater had a negative emotional impact. Further, Simpson and Stratton (2011) found that words such as 'pure' and 'purified' improved confidence, whereas words such as 'recycled' and 'reclaimed' had negative impacts. Unfamiliar terms such as 'potable' actually generated mistrust. With respect to DPR, care may need to be taken to ensure that messages compensate for the perceived loss of the environmental buffer, since the public may respond less favourably to the idea of 'artificial' processes like advanced treatment technologies than 'natural' processes like an environmental buffer (Rozin & Nemeroff, 1990; Nellor & Millan, 2010).

Timing

The timing of messages may also influence the public's attitude to DPR. Attitudes to water recycling tend to solidify over time, indicating the importance of early, accurate information (Ching & Yu, 2010). Hurlimann and Dolnicar (2010) reviewed the failed Toowoomba IPR project and concluded that opponents had benefited from a 'First Mover Advantage'. Because opponents had been the first to communicate with the public, negative information became the benchmark. Over time, it became even more difficult to communicate any positive messages to the public.

However, negative information about water recycling has also been found to be taken seriously by the public no matter whether it was presented before or after positive information about water recycling (Kemp *et al.*, 2012). Kemp *et al.* (2012) suggested that the most likely reason was that, because water is a fundamental human need, any change in supply was likely to be perceived as high risk.

However, Kemp *et al.* (2012) also found that there might be a 'recency effect' with water recycling messages. Attitudes tended to change in the direction of the most recent information campaign. This suggests that water-recycling projects need sustained and frequent positive information campaigns or else public attitudes may be swayed by negative information. Nellor and Millan (2010) advise that water reuse organisations should "never stop your outreach efforts even if the project is successfully under way".

Risk communication

In terms of risk communication, the public may also be strongly influenced by the quality of risk communication by governments and the media, because these outlets have a strong influence on how individuals react emotionally (Mankad, 2012). Media Monitors (2007, p. 26) found that progress in water recycling in Australia was "being stymied by the 'Yuk factor' and political point scoring". Similarly, Hurlimann and Dolnicar (2012) found that Australian newspaper articles on water related topics in 2008 were characterised by a low level of objective information including:

- a lack of inclusion of the position of a broad range of water stakeholders;
- a low level of impartiality; and
- a relatively high level of hedging and the use of words like: suggest; appear; could; might; tentative; uncertain; and most likely.

Knowledge

The US-based Water Reuse Research Foundation recently commissioned and published a research project on the 'Effect of Prior Knowledge of Unplanned Potable Reuse on the Acceptance of Planned Potable Reuse' (Macpherson & Snyder, 2013). This project found that 23 to 28% of Australian and US focus group participants preferred direct drinking water reuse over three other hypothetical reuse scenarios once they understood that drinking water often comes from rivers containing effluent from upstream wastewater treatment plants and agricultural runoff. Keys to acceptance were the language, concepts, and context that researchers used to explain the water cycle and treatment scenarios.

This research explored the hypothesis that approaching the concept of drinking water reuse from an overall urban water cycle context may overcome the stigma and disgust that arises from the typical approach of describing the water as originating in a wastewater treatment plant.

The research involved qualitative focus groups in Sydney, Australia, and in the US in Loudoun County, Virginia; Las Vegas, Nevada; and Hillsboro, Oregon. Focus group participants were shown an informative slideshow presentation entitled 'Downstream', which described the context of urban water management, then illustrated watershed maps depicting real-world catchments in which unplanned potable reuse takes place. Participants were then asked to answer a series of questions about the safety of – and their willingness to drink water from – four potable reuse scenarios presented visually and described to the research participants:

1. 'Current Practice' – drinking water in a community downstream from another community's treated effluent discharge.
2. 'Blended Reservoir' – drinking water sourced from a reservoir that contains river water and water that has been treated at a wastewater treatment plant and a water purification plant.
3. 'Upstream Discharge' – drinking water sourced from a river to which a city's own treated wastewater discharge has been returned upstream of the drinking water intake.
4. 'Direct Potable Reuse' – drinking water sourced directly from a water purification plant after treatment at a wastewater treatment plant, blended in the distribution system with drinking water sourced from a river.

The slideshow in no way obscured the fact that treated, and even untreated, wastewater forms part of the world's drinking water. Participants were assured that regulations were met or exceeded in all the hypothetical reuse scenarios, regardless of whether a water purification plant was included.

The research showed that overcoming linear thinking related to water use appears to help promote acceptance of potable reuse. Water from a planned potable reuse project that included treatment at a water purification plant downstream of a wastewater treatment plant was preferred by survey respondents more than three times as often as water from business-as-usual unplanned potable reuse that did not include a water purification plant.

In a qualitative survey, participants were asked whether they thought that the drinking water in each of the above scenarios was "very safe", "safe", "low safety" or "unsafe". In all four scenarios, a large majority of both Americans and Australians (71 to 90%) thought that drinking water was either "safe" or "very safe".

The second question asked the participants about their willingness to drink the water in each of the four scenarios. They were asked to indicate whether they would be "very willing", "generally OK", "try to avoid" or "refuse" to drink the water. Again, a large majority were either "very willing" or "generally OK" with drinking the water in each scenario (73 to 85%). In both countries, the lowest scores were for Scenario 1 'Current practice'. In all cases, approximately 30% of participants were "very willing" to drink water from scenario 4 'DPR'. Among the key findings was that an awareness that drinking water can come from rivers containing effluent from wastewater treatment plants had an immediate positive impact on the acceptance of planned potable reuse including DPR.

A further finding was that the public appears willing to accept potable reuse, but many want assurances about monitoring processes to know that their drinking water will always be safe. The researchers state that "monitoring and reliability were considered important and, in fact, more important than source water".

An objective assessment of the data collected in this study is that, given the context, people appear to prefer planned IPR compared to either DPR or unplanned IPR. Nonetheless, it is apparent that even DPR is preferred to the current widespread practice of unplanned IPR.

Water recycling visitor centres

Visitors Centres have been a valuable and effective aspect of some successful potable water recycling projects. A well planned Visitors Centre can offer a wide range of opportunities for community engagement and education.

A pioneering example was the Singapore NEWater Visitor Centre, opened in 2003 by Singapore's national water agency, the Public Utilities Board. Interactive models, games and videos are used to describe the water recycling process at a range of levels of technicality. All visitors are presented with a 'bottled water' sample of recycled water on arrival. Through large glass windows, the visitors can see the key components of the advanced treatment process (MF and RO) and observe the plant operators undertaking their duties. The centre caters primarily for a domestic audience, with large numbers of school student tours, but is also a well-advertised attraction for international visitors.

Following the example of Singapore NEWater, educational visitor's centres have been developed adjacent to a number of AWTPs in Australia. Prominent examples include the Gippsland Water Factory located in regional Victoria, Sydney Water's St Marys water recycling plant and Water Corporation's AWTP treating water for the Ground Water Recharge Trial in the northern suburbs of Perth. Each of these hosts visits by school excursions and other interested community members.

In 2009, the City of San Diego established a Water Purification Demonstration Project to examine the viability of a major proposed IPR scheme for that city. Studies examining treatment performance and process reliability were completed in 2013, but the Demonstration Project continues to perform public outreach activities.

None of the existing DPR projects described in Chapter 4 has included a prominent visitor's centre as an aspect of a public outreach or education facility. However, the effectiveness of visitors centres constructed at water recycling plants in Singapore, Australia and the US have demonstrated the potential effectiveness of these facilities for enhancing public engagement and, ultimately, public appreciation and acceptance for the needs and capabilities of these plants.

National Demonstration, Education and Engagement Program

Readers are referred to the Australian Water Recycling Centre of Excellence's National Demonstration, Education and Engagement Program that is currently being developed as part of its Goal 3 research project; 'Reclaimed water is viewed as an acceptable 'alternate water' for augmenting drinking water supplies'.

This project has three streams to its work:

- Stream one is investigating recycled water quality data, the reliability of water recycling treatment technology and an assessment of water recycling schemes in Australia, the US, Europe and Singapore. It aims to show that the whole treatment system from catchment to tap is safe and reliable. It will assess how drinking water schemes using water recycling meet their public health goals.
- Stream two is investigating the perceptions and beliefs of stakeholders and community groups regarding drinking water produced from recycling schemes. It will analyse and make recommendations about how public engagement, decision making processes, governance and institutional arrangements support the successful implementation and development of these types of schemes in Australia.
- Stream three is developing and testing options for a national education and engagement program. The research will consider the extent to which the uptake of drinking water from recycling schemes is being stymied by media-driven panics that fuel an amplified cycle of misinformed public concern,

stigma and political caution. Using relevant case studies, the project will map the influence of traditional media, grassroots community activism, science communication and new media in influencing the community and policy makers. The project will also evaluate the effectiveness of engagement tools, including visitor centres, websites and social media, as well as drawing on international partners' experiences.

Chapter 10 Conclusions

How recycled water for drinking is viewed across Australia depends on several factors, including the management of health risks, cost-effectiveness and public perceptions. Each of these factors will vary across states and regions. Australian communities are entitled to know the costs, benefits and risks involved in all water supply options.

How the benefits of DPR compare to other water supply options, including IPR, seawater desalination, stormwater harvesting and groundwater extraction, will vary across Australia and depend on regional environmental, social and economic factors. In comparing systems, issues to be considered include:

- whether public health and safety can be confidently and reliably met;
- the ability to meet all environmental and health regulatory requirements;
- energy and other costs associated with treating and delivering the water;
- social acceptance of the water source and trust in the water service provider to manage risk; and
- any environmental impacts where the water is sourced and where the wastewater is discharged.

Increasing energy costs may have a significant impact on future decisions to choose between DPR, IPR, surface water dams, or seawater desalination. A cost benefit analysis may identify that an appropriately designed DPR scheme is less expensive to construct and operate than other methods of water supply while still meeting all regulatory requirements.

Public acceptance remains an important and sometimes difficult issue for all planned potable water projects. However, there is evidence to suggest that acceptance is increasing generally and can be fostered by effective engagement and communication programs.

The science, technology and engineering associated with DPR have been rapidly advancing in recent decades. DPR is growing internationally and will be an expanding part of global drinking water supply in the decades ahead.

DPR is technically feasible and can safely supply potable water directly into the water distribution system, but advanced water treatment plants are complex and need to be designed correctly and operated effectively with appropriate oversight. Current Australian regulatory arrangements can already accommodate soundly designed and operated DPR systems.

High levels of expertise and workforce training within the Australian water industry is critical. This must be supported by mechanisms to ensure provider compliance with requirements only to use appropriately skilled operators and managers in their water treatment facilities. This will be no less important for any future DPR implementation and to maintain high levels of safety with current drinking water supply systems.

Some members of the community are concerned about the prospect of DPR. Planning, decision-making, and post-implementation management processes should acknowledge and respond to these concerns. Public access to information and decision-making processes needs to be facilitated. However, the relative merits of water supply options should, as far as possible, be based on quantifiable or evidence-based factors such as public safety, cost, greenhouse gas emissions and other environmental impacts, as well as public attitudes. There is little value in distinguishing DPR from other water supply options, unless specific proposals are compared using these criteria. Any proposal to consider DPR alongside alternative water supply options should explicitly take account of full life-cycle costs, long-term sustainability (including pricing) and full costing of externalities.

Individual recycling schemes, as with other supply options, will present unique opportunities and risks that need to be systematically identified and managed. In ATSE's view, the Australian Guidelines for Water Recycling provide an appropriate framework for managing community safety and guiding responsible decision-making.

Ultimately, water supply decision-making should be based on an objective assessment of available water supply options to identify the most economically, environmentally and socially sustainable solution. While optimum solutions will continue to be case-specific, ATSE is convinced of the technical feasibility and safety of drinking water supply through DPR when properly managed. ATSE considers there may be considerable environmental, economic, and community benefits of supplying highly treated recycled water direct to drinking water distribution systems in appropriate circumstances.

ATSE therefore concludes that DPR should be considered on its merits – taking all factors into account – among the range of available water supply options for Australian towns and cities. Furthermore, ATSE is concerned that DPR has been pre-emptively excluded from consideration in some jurisdictions in the past, and these decisions should be reviewed.

Governments, community leaders, water utilities, scientists, engineers and other experts will need to take leadership roles to foster the implementation and acceptance of any DPR proposal in Australia.

Chapter 11 References

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