Recent Developments in Potable Water Reuse

Jörg E. Drewes and Nils Horstmeyer

Abstract Potable water reuse through the use of treated wastewater effluents has been practiced for more than 50 years. The majority of projects worldwide are characterized as indirect potable water reuse, where an environmental buffer (groundwater aquifer or surface water reservoir) provided retention, additional attenuation, and blending prior to use as drinking water. In order to protect public health, these projects have utilized different treatment processes and combinations to establish multiple barriers against microbial and chemical contaminants. Due to the advancements in environmental analytical chemistry and the recognition of contaminants of emerging concern occurring in reclaimed water that might exhibit adverse health effects, additional advanced treatment processes (including ozone, advanced oxidation, activated carbon) were implemented. With increasing reliability of advanced water treatment processes and operational experience over several decades, the role of the environmental buffer to provide treatment and retention time has been revisited in projects that came online during the last 10 years. Recent trends are favoring direct potable water reuse applications in particular in the USA and Southern Africa that might evolve as the new paradigm for drinking water augmentation using impaired source water. However, questions remain regarding proper protection of public health, reliability and degree of treatment, appropriateness and design of monitoring strategies, maintenance requirements, and cost.

Keywords Contaminants of emerging concern, Environmental buffer, Multiple barriers, Pathogens, Potable water reuse

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Abbreviations

ADD	Acceptable daily dose
AOP	Advanced oxidation processes
BAC	Biologically active activated carbon
BNR	Biological nutrient removal
CA	California
CAS	Conventional activated sludge
CDPH	California Department of Public Health
CEC	Contaminants of emerging concern
DAF	Dissolved air flotation
DALY	Disability-adjusted life years
DEET	*N*,*N*-Diethyl-meta-toluamide
DPR	Direct potable water reuse
EPA	Environmental Protection Agency
EQS	Environmental Quality Standard
EU	European Union
GAC	Granular activated carbon
H_2O_2	Hydrogen peroxide
HAA	Haloacetic acid
IMS	Integrated membrane system
IPR	Indirect potable water reuse
LOD	Limit of detection
MCL	Maximum contaminant level
MF	Microfiltration
NA	Not available
NDMA	*N*-Nitrosodimethylamine
NRC	National Research Council
O_3	Ozonation

PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PNEC	Predicted no-effect concentration
RBAL	Risk-based action level
RBF	Riverbank filtration
RfD	Reference dose
RO	Reverse osmosis
SAT	Soil-aquifer treatment
spp.	Species pluralis
TCEP	Tris(2-chloroethyl) phosphate
TCPP	Tris(1-chloro-2-propyl) phosphate
TDCP	Tris(1,3-dichloro-2-propyl) phosphate
THM	Trihalomethane
TTC	Thresholds of toxicological concern
UF	Ultrafiltration
UncFactor	Uncertainty factor
USA	United States of America
UV	Ultraviolet light
WTP	Water treatment plant
WWTP	Wastewater treatment plant

1 Introduction

Reuse of municipal wastewater – untreated or treated – has been practiced for many centuries with the objective of diverting human waste outside of urban settlements [1]. However, water reuse as a *planned* activity started about one century ago with the use of treated effluent to irrigate Golden Gate Park in San Francisco, California, in 1912 [2]. Non-potable water reuse applications have grown substantially since then from urban landscape irrigation to irrigation of food crops, cooling water, car wash facilities, firefighting, public fountains, stream flow augmentation, to seawater intrusion barriers [3]. With better effluent qualities and scarcity of locally available freshwater supplies, water reuse using treated municipal wastewater effluents has also been considered to augment drinking water supplies as early as the 1960s with pioneering applications in the United States of America (USA) and Namibia. Today, planned potable water reuse is recognized worldwide as an increasingly important component of regional water resource management with a growing number of established projects [4, 5].

Planned potable water reuse projects are characterized as indirect or direct (Fig. 1). Indirect potable water reuse (IPR) is referred to as the purposeful addition of highly treated wastewater (i.e., reclaimed or recycled water) via an environmental buffer that is subsequently used to augment a drinking water supply [5]. The environmental buffers can comprise a groundwater aquifer or a surface water reservoir with the intent to provide retention, additional attenuation of contaminants,

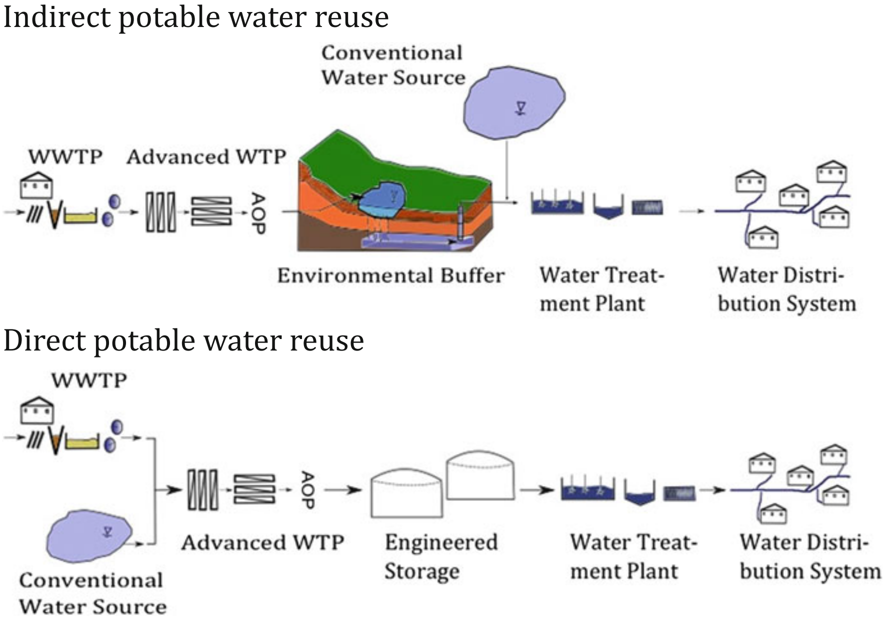


Fig. 1 Conceptual design of indirect and direct potable water reuse applications

and blending prior to use as drinking water. Direct potable water reuse (DPR) is defined as the immediate addition of reclaimed water to a drinking water distribution system or the raw water supply directly upstream of a drinking water treatment facility. In order to provide time to react to any process upset conditions in DPR projects, an engineered storage facility can provide the desired retention time prior to release of the treated water into a distribution system.

In particular during the last 10 years, there is increasing interest worldwide in establishing drinking water augmentation projects using reclaimed water. These initiatives in potable water reuse are driven by population growth; lack of conventional freshwater supplies; competing environmental, industrial, and agricultural needs for water; more frequent and severe drought conditions stressing the availability of conventional freshwater resources; and a higher level of confidence in the efficiency of treatment processes involved.

This chapter describes the current state of potable water reuse practices worldwide including recent advances and trends regarding design and operation of potable water reuse schemes, risk mitigation strategies including water treatment performance goals regarding health risks, the assessment of system reliability, and monitoring strategies for process performance and compliance.

2 The Current State of Potable Water Reuse Applications

2.1 The Evolution of Indirect Potable Water Reuse

Indirect potable water reuse has been practiced in the USA for more than 50 years. In 1962, the pioneering IPR project was established in the Montebello Forebay in Southern California to augment local groundwater supplies with a blend of reclaimed water, stormwater, and imported surface water via surface spreading operation. Severe water scarcity and a lack of alternatives led to the establishment of the first direct potable water reuse project by the City of Windhoek in 1968, which has been replaced by the new Goreangab Water Reclamation Plant in 2002.

In 1976, the Orange County Water District, California, established the Water Factory 21, which was the first IPR facility employing advanced water treatment processes including integrated membrane systems (microfiltration/reverse osmosis) for direct injection projects. Further process evolutions and program expansions in Orange County have resulted in the Groundwater Replenishment System established in 2008, which after completion of a plant expansion in 2015 represents the largest IPR project worldwide with a capacity of 348,000 m^3/day. Potable water reuse projects located in coastal areas in the USA, Singapore, and Australia have favored the use of integrated membrane systems (IMS), in same cases coupled with advanced oxidation processes using ultraviolet light irradiation with hydrogen peroxide (UV/H_2O_2) addition. For inland projects, however, high-pressure membrane filtration is favored less due to the lack of suitable and cost-effective waste stream disposal options. Instead, IPR projects in these locations have employed various combinations of low-pressure membranes (e.g., ultrafiltration), granular activated carbon (GAC) filtration, chemical oxidation (e.g., ozone), and natural treatment systems (e.g., soil-aquifer treatment (SAT), riverbank filtration, wetland treatment) [5, 6]. Table 1 summarizes established potable water reuse projects worldwide.

A range of multiple treatment options and combinations exist, including engineered and natural treatment processes, to design IPR schemes. While these schemes are unified in the goal to lower the risk from microbial and chemical constituents of concern, their individual process treatment efficiency for various contaminants and reliability can vary widely. A similar degree of variability exists regarding the functions of the environmental buffer, including (1) the provision of time to respond to process upsets, (2) attenuation of contaminants, and (3) blending or dilution. While there is ample evidence that an environmental buffer such as soil-aquifer treatment can be very effective regarding these three functions [7, 8], in cases where advanced treatment such as reverse osmosis is employed, additional water quality improvements in a subsequent environmental buffer are marginal at best [9]. Previous studies could not demonstrate that natural barriers provide any public health protection that is not also available by other engineered (above-ground) processes. Thus, the National Research Council (NRC) of the USA

Table 1 Established potable water reuse projects worldwide (adopted from Drewes and Khan [5])

Year	Project	Capacity (m^3/day)	Country	Advanced treatment sequence	Potable water reuse type
1962	Montebello Forebay Spreading Grounds, Los Angeles County Sanitation Districts/ Water Replenishment District, California	165,000	USA	Media filtration-SAT	IPR/groundwater recharge
1968	(Old) Goreangab Water Reclamation Plant, Windhoek	7,000	Namibia	DAF-media filtration-GAC	DPR
1976	Water Factory 21, Orange County Water District, California	60,000	USA	Lime clarification-air stripping-RO-UV/AOP	IPR/seawater intrusion barrier
1978	Upper Occoquan Service Authority, Virginia	204,000	USA	Lime clarification-media filtration-GAC-ion exchange	IPR/surface water augmentation
1985	Hueco Bolson Recharge Project, El Paso, Texas	38,000	USA	Lime clarification-media filtration-ozone-GAC-ozone	IPR/groundwater recharge
1985	Clayton County, Georgia	66,000	USA	UV-wetland	IPR/surface water augmentation
1993	West Basin Water Recycling Plant, California	47,000	USA	Microfiltration-RO-UV/AOP	IPR/seawater intrusion barrier
1999	Gwinnett County, Georgia	227,000	USA	Ultrafiltration-ozone-GAC	IPR/surface water augmentation
1999	Scottsdale Water Campus, Arizona	53,000	USA	Media filtration-microfiltration-RO-UV/AOP	IPR/groundwater recharge
2002	New Goreangab Water Reclamation Plant, Windhoek	21,000	Namibia	Ozone-clarification-DAF-media filtration-ozone-BAC/GAC-ultrafiltration	DPR
2002	Torreele Reuse Plant	7,000	Belgium	Ultrafiltration-RO-UV	IPR/groundwater recharge
2003	NEWater, Bedok	86,000	Singapore	Ultrafiltration-RO-UV	IPR/surface water augmentation

(continued)

Table 1 (continued)

Year	Project	Capacity (m^3/day)	Country	Advanced treatment sequence	Potable water reuse type
2003	NEWater, Kranji	55,000	Singapore	Ultrafiltration-RO-UV	IPR/surface water augmentation
2005	Alamitos Barrier, California	10,000	USA	Ultrafiltration-RO-UV	IPR/seawater intrusion barrier
2007	Chino Basin Recharge Project, California	69,000	USA	Media filtration-SAT	IPR/groundwater recharge
2008	Groundwater Replenishment Project, California	265,000	USA	Microfiltration-RO-UV/AOP	IPR/groundwater recharge/seawater intrusion barrier
2008	Western Corridor Project, Southeast Queensland	232,000	Australia	Microfiltration-RO-UV/AOP	IPR/surface water augmentation (not operational)
2008	Loudon County, Virginia	42,000	USA	Microfiltration-GAC	IPR/surface water augmentation
2009	Arapahoe/Cottonwood, Colorado	34,000	USA	Riverbank filtration-RO-UV/AOP	IPR/groundwater recharge
2010	NEWater, Changi	230,000	Singapore	Ultrafiltration-RO-UV	IPR/surface water augmentation
2010	Prairie Waters Project, Colorado	190,000	USA	Riverbank filtration-softening-UV/AOP-BAC-GAC	IPR/groundwater recharge
2010	Groundwater Replenishment Trial, Perth, Western Australia	5,000	Australia	Ultrafiltration-RO-UV	IPR/groundwater recharge
2011	Cloudcroft, New Mexico	100	USA	Microfiltration-RO-UV/AOP-ultrafiltration-GAC	DPR (not operational)
2012	Dominguez Gap Barrier	10,000	USA	Microfiltration-RO	IPR/groundwater recharge
2012	Beaufort West	1,000	South Africa	Media filtration-ultrafiltration-RO-UV/AOP	DPR

(continued)

Table 1 (continued)

Year	Project	Capacity (m^3/day)	Country	Advanced treatment sequence	Potable water reuse type
2013	Raw Water Production Facility, Big Springs, Texas	7,000	USA	Microfiltration-RO-UV/AOP	DPR
2014	Groundwater Replenishment Project, California (expansion)	348,000	USA	Microfiltration-RO-UV/AOP	IPR/groundwater recharge/seawater intrusion barrier

IPR indirect potable water reuse, *DPR* direct potable water reuse, *DAF* dissolved air flotation, *RO* reverse osmosis, *GAC* granular activated carbon, *BAC* biologically active activated carbon, *AOP* advanced oxidation processes, *UV* ultraviolet light, *SAT* soil-aquifer treatment

concluded that environmental buffers are not essential elements to achieve quality assurance in water reuse projects [10]. As a consequence, the NRC suggested that the classification of potable water reuse projects as indirect (i.e., includes an environmental buffer) and direct (i.e., does not include an environmental buffer) is not meaningful from a technical perspective because the terms are not linked to product water quality [10].

2.2 Trends Toward Direct Potable Water Reuse

Significant technological improvements, operational experience over many decades, and advancements in microbiology, chemistry, and toxicology have resulted in a high degree of confidence in the practice of drinking water augmentation using reclaimed water in the USA [5]. In the early 2010, this confidence level and the impacts from severe droughts, rising energy prices, and requirements for environmental restoration have resulted in a number of initiatives to explore the viability of direct potable water reuse [11]. While some smaller scale DPR projects were recently established in South Africa and the USA primarily driven by severe drought conditions and a lack of alternative supplies (see Table 1), a large initiative was launched in 2010 to advance DPR as a future water supply option for California [6, 12]. In September 2010, reflecting the increased interest in DPR, the Governor of the State of California signed into law Senate Bill 918. This bill mandates 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.

California's Water Recycling Policy has set ambitious goals to increase the total amount of recycled water of currently 802 million m^3/year by a factor of four by 2030. However, especially in Southern California, it has been recognized that further growth of non-potable water reuse in urban settings has reached its limit in many locations and the goal to significantly grow water recycling in the state cannot be met by non-potable water reuse activities. The main limitations of non-potable water reuse are the cost-prohibitive expansion of dedicated dual distribution systems in built-out urban environments and the lack of additional large customers that could be served for non-potable water reuse applications (i.e., public parks, golf courses). Southern California has also relied on imported water from the Colorado River and the State Water Project, which availability has been significantly reduced due to competing environmental needs and declining supplies as a consequence of climate change impacts. Thus, DPR has been recognized in California as a locally sourced, sustainable water supply for the future since it does not require a dedicated dual distribution system and provides cost savings compared to the development and importation of conventional supplies [11, 12]. Nevertheless, there is still a significant gap of knowledge regarding requirements of a fail-safe operation, real-time monitoring, appropriateness of treatment barriers against new contaminants and transformation products, blending options with conventional supplies, and regulatory and public acceptance before DPR can be implemented at a large scale [12].

These trends and developments point to the need to develop better guidance and standardization for the design and operation of potable water reuse schemes including best management practices that can assist the regulatory community and water industry in developing high confidence in fail-safe potable water reuse applications that are protective of public health.

3 Managing Health Risks in Potable Water Reuse

Health risks in potable water reuse applications are associated with microbial and chemical contaminants that can have adverse effects on human health [5]. In addition, aesthetic issues related to taste and odor are also an important consideration for public acceptance of potable water reuse projects [13]. While conventional wastewater treatment in many countries provides an effluent quality that is suitable to be discharged to surface water, treated effluents are still composed of a wide range of naturally occurring and anthropogenic trace organic and inorganic contaminants residual nutrients, total dissolved solids, residual heavy metals, and pathogens [5]. Microbial contaminants including bacteria, viruses, and protozoan parasites are acknowledged as the most critical constituent in reclaimed water due to potential acute human health impacts in public water supplies. Chemical contaminants, of which a large number can still be present in reclaimed water, can be of concern due to potential adverse acute and chronic health effects [10].

In the USA, there are no federal water quality standards for potable water reuse that go beyond drinking water standards under the Safe Drinking Water Act. Four states have developed state-specific regulations or guidelines specifically pertaining to IPR, which differ widely [14]. In 2008, Australia has published the first country national guidelines for the augmentation of drinking water supplies with recycled water, which follow a risk-based approach individual states and territories can adopt [15].

In the European Union (EU), the basis for European water policy is the Water Framework Directive 2000/60/EC [16]. The Directive divides chemical contaminants into priority substances (significant risk to or via aquatic environment) and priority hazardous substances (subset of priority substances, considered to be extremely harmful). While no specific guidelines for potable water reuse currently exist in the EU, water quality standards will likely consider requirements set forth in the Drinking Water Directive (1998/83/EC) [17], the Groundwater Directive (2006/118/EC) [18], and the Environmental Quality Standards Directive (2008/105/EC) [19]. Environmental quality standards (EQS) are currently identified for 45 priority (hazardous) substances with the aim to achieve good chemical status of groundwater and surface waters [19, 20].

As a baseline requirement in any country practicing potable water reuse using reclaimed water, the water quality has to meet drinking water standards. In Europe and the USA, maximum quality standards for drinking water can be used as performance standards for treatment trains; however, they currently only cover less than 100 contaminants potentially also present in reclaimed water. While these include a range of pesticides and industrial contaminants, they do not comprise contaminants that are typically associated with discharges from municipal wastewater effluents, including pharmaceutical residues, personal care products, household chemicals, hormones, or emerging disinfection by-products. Thus, given the origin of reclaimed water, additional water quality requirements acknowledging the impaired quality of the source should be defined where potable water reuse is practiced.

3.1 Setting Water Quality Performance Requirements in Potable Water Reuse

In order to quantify the potential for human health effects as a result of exposure to microbial and chemical contaminants, regulatory agencies have adopted the concept of a “tolerable level of risk” to assist in setting water quality guidelines or standards. In the regulatory realm, *de minimis* risk is defined as a level of risk characterized by the risk being virtually nonexistent to describe risks that are “below regulatory concerns.” Traditionally, for drinking water supplies, *de minimis* risk levels are related to health criteria (i.e., toxicity of the constituent, characteristics of the population, exposure). Different risk levels are commonly used, depending on the specific situation and type of contaminant. The United States Environmental Protection Agency, Office of Drinking Water, uses a “regulatory window” of 10^{-6} to 10^{-4} for the evaluation of risk where 10^{-4} is the baseline risk for all regulations and

10^{-6} is the *de minimis* risk level [21]. Microbial contaminants are regulated at a *de minimis* level of 10^{-4} (where 10^{-4} is the annual individual risk of infection by a given pathogen).

In order to mitigate the acute risk from microbial contaminants, the Australian Water Recycling Guidelines have adopted a numerical definition of safety using 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 [6]. Considering a concentration of selected pathogens in raw sewage and an average daily consumption of two liters per person per year, the log reduction required to achieve compliance with 10^{-6} DALYs per person per year can be calculated using Eq. (1). Removal criteria for pathogenic microorganisms are listed in Table 2.

$$\text{Log reduction} = \log((\text{source concentration} \times 2\,\text{L} \times 365\,\text{days})/\text{DALYd}), \qquad (1)$$

where DALYd (the dose equivalent to 10^{-6} DALYs) for *Cryptosporidium* is 1.6×10^{-2}, for enteric viruses is 2.5×10^{-3}, and for *Campylobacter* is 3.8×10^{-2} [6].

Performance goals for potable water reuse projects in California have been proposed that are based on a low tolerable or *de minimis* risk level of 10^{-4} annual risk of infection and occurrence data of pathogens in raw wastewater [22].

In order to meet these requirements, a given potable water reuse treatment train has to demonstrate that the additive removal efficiencies for microbial contaminants provided by individual treatment processes can meet the desired overall log removal criteria. Meeting this goal would ensure that the reclaimed water is free of pathogenic microorganisms with a large margin of safety and could be safely used for potable purposes. The reason for this rather high degree of conservatism is the lack of comprehensive occurrence data for pathogenic microorganisms in raw sewage.

Table 2 Removal criteria for pathogenic microorganisms for the evaluation of potable water reuse schemes (adopted from [6, 22])

Microbial group	Criterion ($\log_{10}$ removal) California	Criterion ($\log_{10}$ removal) Australia	Possible surrogates	Notes
Enteric virus	12	9.4	MS-2 bacteriophage	
Cryptosporidium spp.	10	8	Inactivated *Cryptosporidium oocysts*, aerobic spores	Addresses also *Giardia* and other protozoa
Total coliform bacteria	10	NA	NA	Addresses also enteric pathogenic bacteria
Campylobacter	NA	8.1		

For the evaluation of potable water reuse treatment schemes regarding chemical contaminants, the following factors need to be considered:

- The contaminant chosen to assess treatment performance must occur frequently enough and at a concentration significantly above the analytical method detection limit.
- Appropriate and commercially available analytical methods exist for the quantification of target contaminants in reclaimed water.
- Targeted contaminants for monitoring programs should be broadly representative of both the varying types of contaminants of health concern ("indicator contaminants with health relevance") and the wide range of physicochemical and biological properties that affect their removal of various unit processes within a potable water reuse treatment train ("performance indicator contaminants to assess treatment efficacy").
- The establishment of multiple treatment barriers with different removal mechanisms (i.e., chemical oxidation, biological treatment, physical separation) provides robustness against a wide range of currently not yet identified contaminants.

Performance goals for chemical contaminants for a proposed potable water reuse scheme will include contaminants of recognized health concern that have published guideline values or standards. These include regulated contaminants with an acceptable health risk specified, for example, as drinking water standards in the EU Water Framework Directive, the EPA maximum contaminant levels (MCLs) in the USA, chemical guideline values in the Australian Water Recycling Guidelines, WHO Drinking Water Goals, or EPA health advisories or health reference levels. For unregulated contaminants with known toxicological information, the *de minimis* risk approach can be used. In order to specify *de minimis* benchmarks for these contaminants, a reference dose (RfD), acceptable daily dose (ADD), or predicted no-effect concentration (PNEC) information expressing their toxicological relevance can be adopted [6, 23–26]. These benchmarks are considered in a risk-based action level (RBAL) following a framework proposed by the WHO [27] and the USA National Research Council [19] for chemical exposure via drinking water (considering a relative source contribution of 0.2):

$$\mathrm{RBAL},\ \mu\mathrm{g/L} = \frac{\left(\mathrm{Benchmark}, \frac{\mu\mathrm{g}}{\mathrm{kg} \times d}\right) \times 60\,\mathrm{kg} \times 0.2}{2\,\mathrm{L}/d \times \mathrm{UncFactor}}, \tag{2}$$

where neither existing guideline values nor relevant toxicological data to develop benchmark values are available; a quantitative structure-activity relationship approach can be used as a method for deriving thresholds of toxicological concern (TTCs) [6]. The TTC approach is based upon the statistical evaluation of a large group of chemicals with similar structure and functional groups. It allows to identify a 95 percent lower confidence level for chronic no adverse effect level and then apply uncertainty factors similar to noncancer risk assessments. The use of TTCs is well established internationally and has been used by the USA Food and

Table 3 Health-based indicator contaminants of interest proposed for monitoring programs of potable water reuse projects (adopted from [22, 29, 30])

Chemical	Criterion	Note
N-Nitrosodimethylamine (NDMA)	10 ng/L	California reporting level
Trihalomethanes (THMs)	60 μg/L	MCL of USA EPA
Haloacetic acids (HAAs)	80 μg/L	MCL of USA EPA
Bromate	10 μg/L	MCL of USA EPA; EU
Chlorate	700 μg/L	WHO
Perfluorooctanoic acid (PFOA)	0.4 μg/L	Provisional EPA Health Advisory
Perfluorooctanesulfonic acid (PFOS)	0.2 μg/L	Provisional EPA Health Advisory
Perchlorate	15 μg/L	EPA Health Advisory
1,4-Dioxane	1 μg/L	California notification level
Simazine	4 μg/L	MCL of USA EPA
2,3-Dichlorophenoxyacetic acid (2,4-D)	70 μg/L	MCL of USA EPA
17β-Estradiol	0.9 ng/L	Monitoring trigger level
Triclosan	350 ng/L	Monitoring trigger level

Drug Administration and the WHO for setting guidelines for minor contaminants. A similar approach has been proposed by the German EPA (Umweltbundesamt) to derive public health advisory values and precautionary values for contaminants of emerging concern [28]. Precautionary values for unregulated contaminants with insufficient toxicological data usually are assigned a blanket value of 0.1 $\mu g L^{-1}$.

Given the large number of contaminants, deviations in published RfD or PNEC values for individual contaminants, and differences in expert opinion regarding appropriate uncertainty factors (UncFactor) for carcinogenic contaminants, a uniform list of contaminants that should be monitored in potable water reuse schemes does not yet exist. Nevertheless, several scientific groups and panels have proposed contaminants with human health relevance to be used in monitoring programs of potable water reuse projects [22, 29, 30]. Table 3 lists proposed health-based indicator contaminants for potable water reuse projects.

Performance validation and verification of established and alternative treatment trains can occur through direct measurements of indicator contaminants representing a variety of structures and physicochemical properties that correlate with the core removal mechanisms (i.e., biotransformation, adsorption, size exclusion, chemical oxidation) of individual unit processes [31–33]. In addition, the removal of specific performance-based indicator contaminants or families of contaminants with closely related properties may be correlated with the removal of other routinely measured compounds or operational parameters that can be monitored continuously as a surrogate parameter (e.g., electrical conductivity, UV absorbance) [31, 34, 35]. These approaches have the advantage that they can be established as real-time monitoring strategies where a high resolution of system performance control is desired. Table 4 summarizes proposed maximum concentrations of performance-based indicator contaminants and expected removal percentages for monitoring of treatment train efficacy of potable water reuse projects.

Table 4 Performance-based indicator contaminants proposed for monitoring programs of potable water reuse projects (adopted from [22, 26, 30])

Chemical	Criterion (max. concentration or minimum percent removal)	Note
Atenolol	4 μg/L	[26]
Caffeine	350 ng/L 90%	Monitoring trigger level [30] Removal by SAT or RO/AOP treatment [30]
Carbamazepine	100 μg/L	[26]
DEET	200 μg/L 90%	[26] Removal by SAT or RO/AOP treatment [30]
Dilantin	50 μg/L	[26]
Gemfibrozil	90%	Removal by SAT [30]
Iopromide	90%	Removal by SAT [30]
Meprobamate	200 μg/L	[26]
Primidone	375 μg/L	[26]
Sucralose	None 25% 90%	Approved for use as a sweetener in food Removal by SAT [30] Removal by RO/AOP treatment [30]
TCEP	5 μg/L	Monitoring trigger level, State of Minnesota guidance value [26, 30]

4 Design Principles of Potable Water Reuse

The core design elements of potable water reuse treatment trains involve a thorough understanding of source water characteristics, the establishment of reliable treatment systems, storage and blending considerations, and an overarching monitoring program for performance and compliance (Fig. 2). These elements are further discussed in the sections below.

4.1 Monitoring Program for Performance and Compliance

Monitoring programs for potable water reuse projects need to be considered and designed to address source control and treatment performance assessments, assuring that specified finished water quality criteria are met. Assessing treatment train performance and compliance and finished water quality criteria have been discussed in previous sections. Source control requirements are being addressed in the next section. Additional information can be found in Drewes and Khan [5].

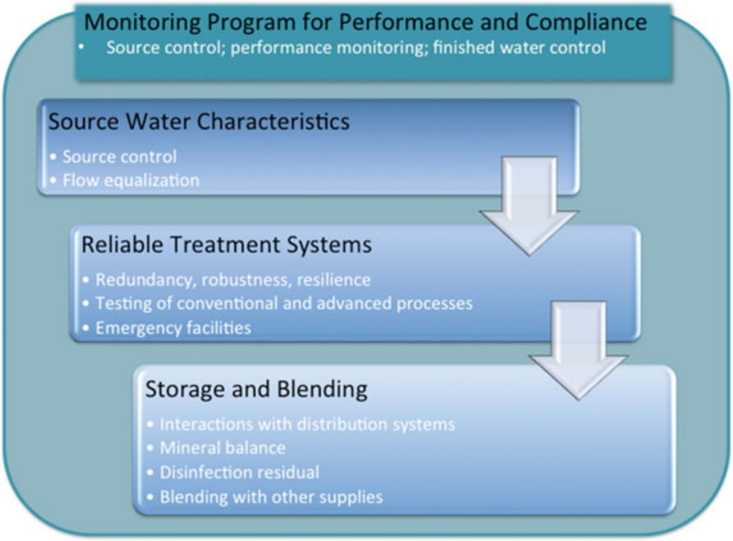


Fig. 2 Key design elements of potable water reuse schemes

4.2 Source Water Characteristics

Understanding the variability of source water quality is a prerequisite to properly design efficient processes for a potable water reuse treatment train. Besides treatment processes, flow equalization measures can be effective in mitigating and eliminating significant differences in source water quality and quantity. In particular for DPR project, flow equalization is an important design feature that can result in both a more consistent source water quality and a more homogeneous load to downstream treatment processes, in general contributing to a more consistent finished water quality.

In addition, source control through monitoring and compliance assessments of point discharges to the sewer system is a critical element to maintain a consistent reclaimed water quality [5, 6]. These programs are conducted with the goal of reducing treatment costs, targeting inorganic and organic contaminants of concern that are not primarily removed during conventional wastewater treatment (i.e., heavy metals, trace organic contaminants), and therefore improving the reliability of the final water quality.

4.3 Reliable Treatment Systems

Any potable water reuse scheme should be designed to reliably supply a finished water quality that is safe for human consumption at all times. System reliability of a potable water reuse project is defined as the probability of adequate performance for a specified period of time under predefined conditions. Reliability in potable water reuse systems can be achieved by a number of supporting concepts including redundancy, robustness, and resilience.

The concept of redundancy describes the use of multiple barriers to control acute risks. Robustness is defined as the capacity to remove a wide range of particular chemical contaminants. In addition, potable water reuse facilities must also be resilient to ensure reliability even under rare failure events. A resilient system in this respect is not a system that never fails, but a system that fails safely, meaning that failures are mitigated through well-designed response plans including the prevention of distributing water that does not meet specified requirements. System reliability requirements may include standby power supplies, provisions for alarms, readily available replacement equipment, online monitoring of system performance and water quality, redundant process components that are critical for the protection of public health, flexible piping and pumping configurations, trained personnel, and emergency storage or disposal options.

Combining water treatment processes that are capable of providing effective, reliable, and redundant barriers to pathogens and contaminants are referred to as the *multiple-barrier approach* to water treatment. For potable water reuse projects, although the multiple barriers do tend to be relied on to provide cumulative steps toward the achievement of overall treatment goals, there is generally an expectation that they will accommodate a degree of treatment redundancy for pathogens. That is, the protection of public safety will be maintained even if a single treatment barrier fails. The independence of multiple barriers is a key aspect of system reliability and safety. In order to mitigate the acute risk from microbial contaminants and to meet overall removal criteria as discussed earlier (see Table 2), various unit processes can be combined in a meaningful fashion considering conservative expected log removal efficiency of individual unit processes for pathogenic microorganisms as specified in Table 5 [36].

Table 5 Log removal efficiencies of various unit processes to remove target microbial contaminants (adopted from [36])

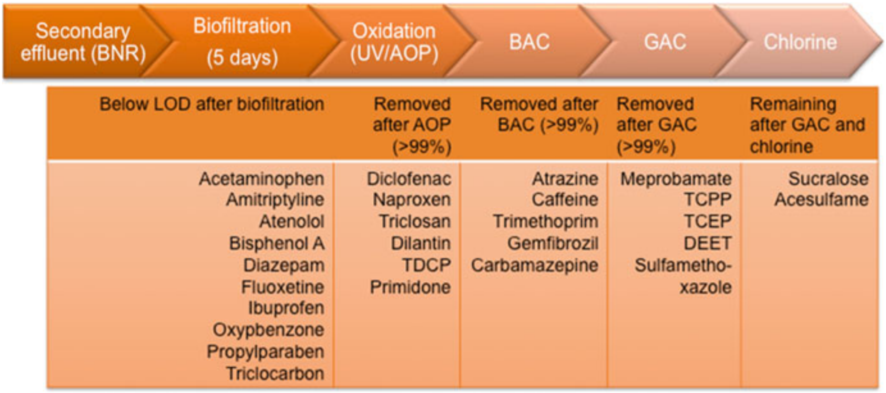
Unit process	Enteric viruses	*Cryptosporidium*	Total coliform bacteria
Conventional activated sludge (CAS)	1	0	2
Microfiltration (MF)	0	4	4
Ultrafiltration (UF)	1	4	4
Reverse osmosis (RO)	2	2	2
Ozonation (O_3)	6	1	4
Biologically active activated carbon (BAC)	0	0	0
Ultraviolet light (UV)	6	6	6
UV light with hydrogen peroxide (UV/AOP)	6	6	6
Free chlorine	3	0	4

For an IPR scheme typically designed for direct injection into a potable aquifer, accumulative virus log removal efficiencies for enteric viruses would total 22 (Fig. 3). An IPR treatment train with very short retention in an environmental buffer consisting of biofiltration via subsurface treatment, advanced oxidation, and activated carbon treatment followed by final disinfection prior to blending with conventional supply would achieve an overall virus log removal efficiency of 12 (Fig. 4). Both treatment combinations would also exceed the required log removal criteria for cryptosporidium and total coliform bacteria (data not shown). Given that the proposed log removal criteria are already very conservative (Table 2), the margin of safety that potable water reuse projects utilizing treatment combinations as illustrated in Figures 3 and 4 can provide against pathogenic contaminants will likely exceed conventional drinking water supplies that are using source water receiving small amounts of wastewater discharge (exceeding a contribution of 5%) by several orders of magnitude [10].

Given the wide range of different contaminants present in reclaimed water, robust multiple barriers should be designed to consider a sequence of diverse processes that are capable of targeting the wide range of physicochemical properties represented by various classes of contaminants. The requirement for redundancy normally associated with pathogen removal is not applied to multiple barriers for chemicals. This is because exposure to chemicals is more of a chronic risk, relating to long-term exposure, as compared with the acute risks associated with pathogens, for which even short-term exposure may have significant impacts on human health. Thus, for the removal of chemical contaminants, diversity in treatment rather than redundancy can result in highly efficient overall removal of trace organic contaminants generating a finished water quality that is indistinguishable to conventional supplies (Fig. 5).

Fig. 3 Virus log removal efficiency by a potable water reuse treatment train consisting of integrated membrane systems followed by advanced oxidation processes and an environmental buffer

Fig. 4 Virus log removal efficiency by a potable water reuse treatment train consisting of biofiltration via subsurface treatment, advanced oxidation, and activated carbon treatment followed by final disinfection prior to blending with conventional supply



Below LOD after biofiltration	Removed after AOP (>99%)	Removed after BAC (>99%)	Removed after GAC (>99%)	Remaining after GAC and chlorine
Acetaminophen	Diclofenac	Atrazine	Meprobamate	Sucralose
Amitriptyline	Naproxen	Caffeine	TCPP	Acesulfame
Atenolol	Triclosan	Trimethoprim	TCEP	
Bisphenol A	Dilantin	Gemfibrozil	DEET	
Diazepam	TDCP	Carbamazepine	Sulfamethoxazole	
Fluoxetine	Primidone			
Ibuprofen				
Oxypbenzone				
Propylparaben				
Triclocarbon				

Fig. 5 CEC removal efficiency by a potable water reuse treatment train consisting of biofiltration via subsurface treatment, advanced oxidation, and activated carbon treatment followed by final disinfection prior to blending with conventional supply (Note: concentrations for the artificial sweetener sucralose and acesulfame in the finished water where in the elevated ng/L range were well below any health relevance level)

4.4 Storage and Blending

The water quality after advanced treatment requires adjustments in particular where different source waters are blended regarding compatibility with the drinking water distribution system (i.e., saturation index, corrosivity) and aesthetics (i.e., mineral balance, color). In IPR systems, storage and blending can occur by passing water through an environmental buffer. In many potable water reuse systems, however, the primary benefit of environmental buffers is to provide time to respond to an inadequate water quality associated with inappropriate treatment or other factors [5]. Thus, in the context of DPR projects, an engineered storage unit or adequate (real-time) monitoring systems (or both) might be able to fulfill the function of the environmental buffer. However, additional research is needed to develop specific storage and blending requirements for DPR projects.

5 Energy Requirements

An important consideration besides water quality aspects for the implementation of potable water reuse schemes is the energy footprint associated with different supply options including reuse. While the energy footprint of potable water reuse schemes mainly depends on the type and sequence of individual unit processes, the energy requirements of alternative water supply options are much dependent upon local conditions, in particular when it comes to reliance on imported water.

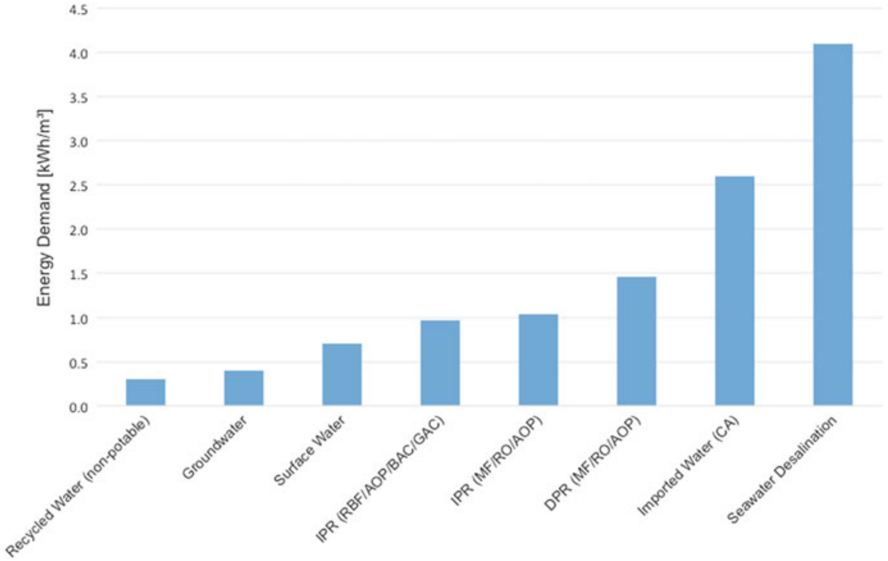


Fig. 6 Specific energy requirements for conventional and alternative water supply options based on the estimates for California (adopted from [10, 12])

Specific energy data for various supply options for California summarized in Fig. 6 illustrates that potable water reuse either indirect or direct can represent very cost-effective supply alternatives to ocean desalination and use of imported water. Different treatment train configurations for potable water reuse schemes should be investigated to further decrease the energy footprint, in particular where energy-intense processes are employed (i.e., high-pressure membranes, advanced oxidation processes).

6 Conclusions

The practice of potable water reuse has evolved over the last 50 years into a viable option for an integrated water resource management to safely augment drinking water supplies with recycled water. Today, potable water reuse is also practiced in locations that are not characterized by arid or semiarid climate conditions, but regions that experience seasonal water shortage or have a desire to diversify their water resource portfolio for future climate change impacts.

While there is also increasing recognition that unplanned or de facto potable water reuse is occurring where treated wastewater effluents are discharged to surface water that subsequently serves as a source of drinking water, proper safeguards to mitigate the risks associated with microbial and chemical contaminants is not always appropriately addressed [10, 37]. Thus, best management practices and risk management frameworks developed for potable water reuse projects as described in this chapter might also provide guidance for de facto potable water reuse situations.

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