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# Contemporary design, operation, and monitoring of potable reuse systems

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## ABSTRACT

Water scarcity driven by population growth, lack of conventional supplies, and climate change impacts have resulted in increasing interest worldwide in drinking water augmentation using treated wastewater effluents. Potable reuse can occur indirect or direct, but is also practiced in many places as 'de facto reuse', where upstream wastewater discharge occurs to drinking water supplies. With this increasing recognition of potable reuse, there is very limited guidance and standardization for proper design and operation of potable reuse schemes that is protective of public health. This study provided guidance on contemporary approaches for the design, operation, and monitoring of potable reuse schemes, including source water characterization and source control approaches; linking water quality treatment performance goals to health risks; risk mitigation strategies including the design principles of multiple barriers for microbial and chemical contaminants; assessing system reliability and fail-safe design approaches; and, finally, monitoring strategies for process performance and compliance.


**Key words** | chemicals of emerging concern, design principles, health risks, multiple barriers, pathogens, potable reuse

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## INTRODUCTION

With scarcity of locally available water supplies in many regions of the world, impacts from severe droughts, rising energy prices, the need to mitigate for greenhouse gas emissions and requirements for environmental restoration, the use of unconventional water supplies is becoming an increasingly important component of water resource management worldwide (Daigger 2009). The practice of using an unconventional water resource, which has been recycled from treated wastewater to beneficial purposes, is commonly referred to as water reuse. Water reuse to supplement drinking water supplies is referred to as 'potable water reuse'. Planned potable water reuse can be categorized as indirect potable reuse (IPR) or direct potable reuse (DPR) depending on the way in which the recycled water is stored and used. The term IPR is used to describe cases involving the purposeful addition of recycled water to a natural water source, such as a groundwater aquifer or surface water reservoir, from which a drinking water supply is drawn. The natural water source provides an environmental buffer (Drewes & Khan 2011). The term DPR is used to describe cases where recycled water is added directly to a water distribution system or to a source water system immediately upstream of a drinking water treatment plant, without any environmental buffer. A separate category of 'de facto potable reuse' can be used to describe cases in which a drinking water source contains a significant fraction of recycled water discharged from wastewater treatment plants in the upstream watershed, although the supply has not been permitted as a water reuse project (NRC 2012). There is no clear threshold that constitutes de facto potable reuse, but there is an increasing recognition that this practice does occur in many locations to a degree where management and treatment approaches employed in planned potable reuse are warranted.

IPR has been practiced in the United States for more than 50 years and significant technological improvements,

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long-term operational experience, and advancements in microbiology, toxicology, and chemical analysis have provided a high degree of confidence in this practice of drinking water augmentation (Drewes & Khan 2011; Tchobanoglous *et al.* 2011). DPR was first established in 1969 with the Goreangab water reclamation plant in Windhoek, Namibia providing a safe supply until today (Du Pisani 2006). After a major upgrade in 2002, it is evident from the Windhoek experience that treated domestic sewage can be successfully recycled for potable purposes. This confidence level from various planned potable reuse schemes has resulted in a number of recent initiatives to also explore DPR projects in the USA and elsewhere (Tchobanoglous *et al.* 2011; Khan 2013). These activities include the establishment of a few full-scale DPR projects during the last three years and regulatory initiatives, such as Senate Bill 918, which requires the California Division of Drinking Water to investigate the feasibility of developing regulatory criteria for DPR in California by 2016 (Tchobanoglous *et al.* 2011).

While planned and unplanned (or de facto) potable reuse can potentially be a viable option for drinking water augmentation, very limited guidance and standardization exist for the design, operation, and compliance monitoring of this engineering practice (NRC 2012). This study has identified contemporary approaches and principles for the management of recycled water quality and for the design, operation, and monitoring of potable reuse schemes including best management practices that can assist the water reuse industry and regulatory community to develop confidence in potable reuse applications while protecting public health.

## WATER QUALITY CONCERNS RELATED TO POTABLE REUSE

### Chemical and microbial contaminants of concern

Microbial and chemical contaminants including regulated and unregulated parameters are the primary categories of constituents that are related to human health impacts. In addition to health-related considerations, esthetic issues are also an important consideration for the public acceptance of a potable reuse project. Microbial contaminants in reclaimed water can include bacteria, viruses, and protozoan parasites. Pathogenic microorganisms (microorganisms that can cause disease in a host) are widely acknowledged as the most critical element with respect to potential acute impacts on human health in public water supplies (Drewes & Khan 2011). Most bacteria associated with waterborne diseases are relatively susceptible to chemical disinfection practices such as chlorination, chloramination, or ultraviolet irradiation. Viruses typically are more resistant to environmental stresses than bacteria. Numerous studies have used viruses as model organisms to determine the fate of microorganisms because viruses can be more resistant to disinfection processes than bacteria and are smaller in size, which makes them more difficult to remove by granular media or membrane filtration.

The US EPA estimates that over 85,000 chemicals can potentially be present in reclaimed water with a broad range of sources, characteristics, and concentrations (Drewes *et al.* 2013). Chemical contaminants can be of concern for acute and chronic exposure effects. Additionally, naturally occurring inorganic chemicals and salts that are present in source water and the addition of water and wastewater treatment chemicals impact the quality of reclaimed water sources. The risks from these contaminants must be mitigated through the selection of diverse treatment processes that are suitable to remove these chemicals effectively.

### Human health risks in potable reuse

Risk, not just from exposure to microbial and chemical contaminants, is inherent in all human activities. In order to quantify the potential for human health effects as the result of an environmental action, a risk analysis can be conducted and usually is structured into risk assessment and risk management. Risk assessment, which includes an analysis of the potential effect of certain hazards to human health, includes the following four steps: hazard identification, exposure assessment, dose response assessment, and risk characterization (Drewes & Khan 2011). Risk management includes the development of standards, guidelines, and management strategies for specific constituents.

Regulatory agencies have adopted the concept of a 'tolerable level of risk' to assist in setting water quality guidelines or standards. In such cases, health targets are adopted to reflect an accepted tolerable risk level, which could be expressed in a variety of ways. *De minimis* risk, which is defined as a level of risk characterized by the risk being virtually non-existent, is often used in the regulatory realm to describe risks that are 'below regulatory concern'. Traditionally, for drinking water supplies, *de minimis* risk levels are related to health criteria (toxicity of the constituents, the characteristics of the population, and exposure). Different risk levels are used, depending on the specific situation and type of contaminant. The US EPA Office of Drinking Water uses a 'regulatory window' of $10^{-6}$ to $10^{-4}$ for evaluation of risk where $10^{-4}$ is the baseline risk for all regulations and $10^{-6}$ is the *de minimis* risk level. 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).

## DESIGN AND OPERATION PRINCIPLES FOR POTABLE REUSE

The core design features of potable reuse schemes are illustrated in Figure 1 and further explained in the sections below.

### Well-defined source water characteristics and source control

Conventionally treated municipal effluents are composed of a wide range of naturally occurring and synthetic, trace organic and inorganic chemicals, residual nutrients, dissolved solids, and residual heavy metals, as well as pathogens. The composition of chemical contaminants is unique for every reclaimed water source at any given time. Since general water quality characteristics of reclaimed water deviate from those of conventional drinking water sources, compliance with established drinking water standards as promulgated by the Safe Drinking Water Act by conventionally treated and reclaimed wastewater does not imply that the reclaimed water is safe for human consumption (Drewes & Khan 2011). Municipal wastewater effluent quality is also subject to temporal changes and the size of the sewershed served (Ort *et al*. 2010a, b; Teerlink *et al*. 2012). Thus, it is important to understand this variability and properly characterize the source water quality. Water treatment processes employed in potable reuse schemes must be capable of mitigating and eliminating these differences.

In addition, source control through monitoring and compliance assessments of point discharges to the sewer

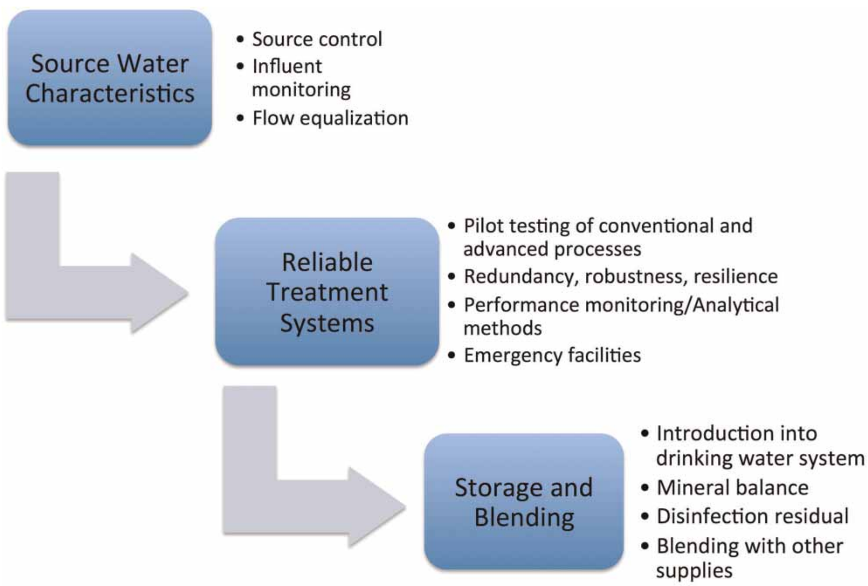


**Figure 1** | Design elements of potable reuse schemes.

system are a critical element to maintain a consistent water quality. These programs are conducted with the goal of reducing treatment costs, targeting chemicals of concern that are not primarily removed during conventional wastewater treatment (i.e., heavy metals, trace organic chemicals) and therefore improving the reliability of the final water quality. In particular for DPR projects, flow equalization is an important design feature that can provide both a more consistent source water quality and a more homogeneous load to downstream treatment processes, in general resulting in more consistent finished water qualities.

## 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 potable reuse project is defined as the probability of adequate performance for a specified period of time under predefined conditions. Reliability in potable 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 particularly chemical contaminants. In addition, potable 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.

Several factors affect system reliability: (1) the variability of wastewater characteristics; (2) the inherent variability of conventional (i.e., biological) treatment processes; (3) the inherent variability of advanced water treatment processes; (4) the reliability of mechanical plant components; and (5) the effectiveness of monitoring (Asano *et al.* 2007). 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.

The integration of water treatment processes that are capable of providing effective, reliable, and redundant barriers to pathogens and chemicals is referred to as the 'multiple-barrier approach' to water treatment. For potable 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 (National Research Council 1998). In the case of chemicals, the expectation is that a series of treatment steps will be used to reduce the overall chemical load. Given the wide range of different chemicals present in reclaimed water, robust multiple barriers should be designed to consider a sequence of diverse processes that are capable of targeting classes of chemicals encompassing different physicochemical properties. 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. From a public health standpoint, adequate and effective disinfection is the most essential process element that requires the highest degree of reliability and need for redundancy. The independence of multiple barriers is a key aspect of system reliability and safety.

## Performance goals

The water quality of any potable reuse project using reclaimed water in the United States has to meet the drinking water standards as promulgated by the US EPA. While these maximum contaminant levels can be used as performance standards, they currently only cover about 90 contaminants potentially present in reclaimed water. These include a range of pesticides and industrial chemicals, but not chemicals that are associated with discharges from municipal wastewater effluents, such as pharmaceutical residues, personal care products, household chemicals, steroidal hormones, or emerging disinfection by-products. Thus, considering the origin of reclaimed water, additional water quality requirements for potable reuse are needed.

In order to mitigate the acute risk from microbial contaminants, performance goals 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 (NWRI 2013; DDW 2014). These criteria for key pathogenic microorganisms are summarized in Table 1.

Performance goals for the chemical contaminants for a proposed potable reuse scheme might consider their toxicological relevance if this information is readily available (Schwab *et al.* 2005; Snyder *et al.* 2008; Drewes *et al.* 2013). Published research on the mechanisms through which treatment processes act indicates that it should be possible to predict the extent of compound removal for compounds (termed 'indicators') exhibiting similar properties provided that those properties determine the behavior of the compound in the treatment process (Drewes *et al.* 2013). Furthermore, the removal of specific compounds or families of compounds with closely related properties may be correlated with the removal of other routinely measured compounds or operational parameters (termed 'surrogates') that can be monitored continuously (e.g., conductivity, UV absorbance) (Drewes *et al.* 2008, 2010; Wert *et al.* 2009).

Performance validation and verification of established treatment processes and compliance water quality monitoring are the most important aspects of overall system reliability. These approaches include real-time monitoring strategies for chemical and microbial contaminants of human health relevance. The system performance variability should be well understood resulting in a system reliability that can be quantified ('fail-safe' design approach). These efforts involve a hazard analysis, determination of critical control points and critical limits, as well as a catalog of corrective actions if a critical control point is not working properly (Drewes & Khan 2011; NRC 2012).

**Table 1** | Removal criteria for pathogenic microorganisms for the evaluation of potable reuse schemes

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

## Role of the environmental buffer

Environmental buffers in potable reuse schemes can provide additional treatment and blending with other sources of waters (native groundwater and surface water), but the primary benefit is to provide time to react to an inadequate water quality associated with inappropriate treatment or other factors (Drewes & Khan 2011). Where advanced treatment is applied (i.e., reverse osmosis followed by advanced oxidation processes), water quality benefits achieved by additional retention in an environmental buffer are minor, if any. Thus, especially in the context of DPR it is being discussed how the function of the environmental buffer can be replaced by engineered (storage) solutions or/and improved (real-time) monitoring systems (Khan 2013).

## Public perception

Although these technical components are important for any proposed potable reuse project, addressing the psychological dimension of potable reuse is essential for a successful project. In several cases over the last 15 years, this aspect of potable reuse evolved as the determining factor for success or failure of a project and outweighed the technical merit of some proposed projects resulting in their termination prior to completion. It is widely recognized that the ultimate success of any potable reuse project is determined by the level of public and key stakeholder acceptance. Successful case studies of IPR via surface water augmentation and groundwater recharge are described in Drewes & Khan (2011).

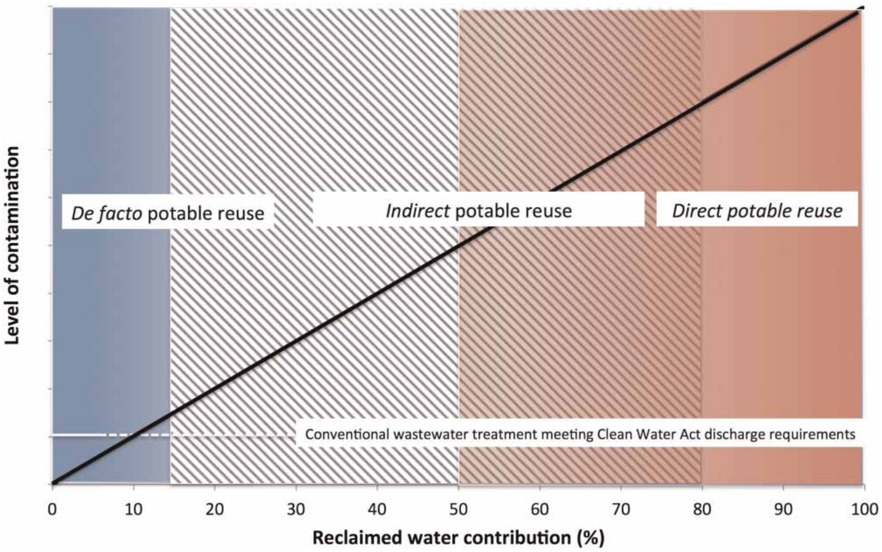


**Figure 2** | The continuum of potable reuse practices.

## CONCLUSIONS

Long-term experience in operating treatment schemes over several decades in several locations has increased the confidence in the practice of water reuse leading to drinking water augmentation. This practice has resulted in core design and operational requirements that, in particular, address the remaining risks from microbial and chemical contaminants. As more and more projects are being implemented, the difference between indirect and DPR becomes indistinct (Figure 2). In locations where de facto potable reuse above a reclaimed water contribution of a few percentages is practiced, the design and operational principles of planned potable reuse projects as described in this study should be adopted.

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