Direct potable reuse: a future imperative

Harold L. Leverenz, George Tchobanoglous and Takashi Asano

ABSTRACT

As a result of population growth, urbanization, and climate change, public water supplies are becoming stressed, and the chances of tapping new water supplies for metropolitan areas are getting more difficult, if not impossible. As a consequence, existing water supplies must go further. One way to achieve this objective is by increased water reuse, particularly in supplementing municipal water supplies. Although water reuse offers many opportunities it also involves a number of problems. A significant cost for nonpotable water reuse in urban areas is associated with the need to provide separate piping and storage systems for reclaimed water. In most situations, the cost of a dual distribution system has been prohibitive and thus, has limited implementation for water reuse programs. The solution to the problem of distribution is to implement direct potable reuse (DPR) of purified water in the existing water distribution system. The purpose of this paper is to consider (a) a future in which DPR will be the norm and (b) the steps that will need to be taken to make this a reality. Following an overview, the rationale for DPR, some examples of DPR projects, technological and implementation issues, and future expectations are examined.

Key words | direct potable reuse, engineered storage buffer, potable reuse, water reuse

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DIRECT POTABLE REUSE: AN OVERVIEW

Direct potable reuse (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 even direct pipe-to-pipe blending of purified water and potable water. DPR offers the opportunity to significantly reduce the distance that purified water would need to be pumped and significantly reduce the head against which it must be pumped, thereby reducing costs. The other significant advantage of DPR is that it has the potential to allow for full reuse of available purified water in metropolitan areas, using the existing water distribution infrastructure.

A general flow diagram for alternative potable reuse strategies is shown on Figure 1. As shown, two DPR options are available. In the first option (heavy solid black line), purified water is first placed in an engineered storage buffer (ESB). From the ESB, purified water can either be blended with the water supply source prior to water treatment or can be blended directly with treated potable water. In the second option (heavy dashed back line) purified water, without the use of an ESB, can be blended in either of the two locations discussed for option 1. As will be discussed later, implementation of option 2 would entail more extensive reliability measures and effective on-line continuous monitoring. The concept and role of the ESB is considered in the following discussion.

Engineered storage buffers for quality assurance

An important element of a DPR system is the ability to provide water of a specified quality reliably all the time. Because of the past limitations in providing this level of quality control in real-time and the large number of unknown factors, there was a preference for indirect potable reuse (IPR) projects instead of DPR projects. IPR systems make use of an environmental buffer, such as a surface reservoir or groundwater basin, to store water and ostensibly provide enhanced

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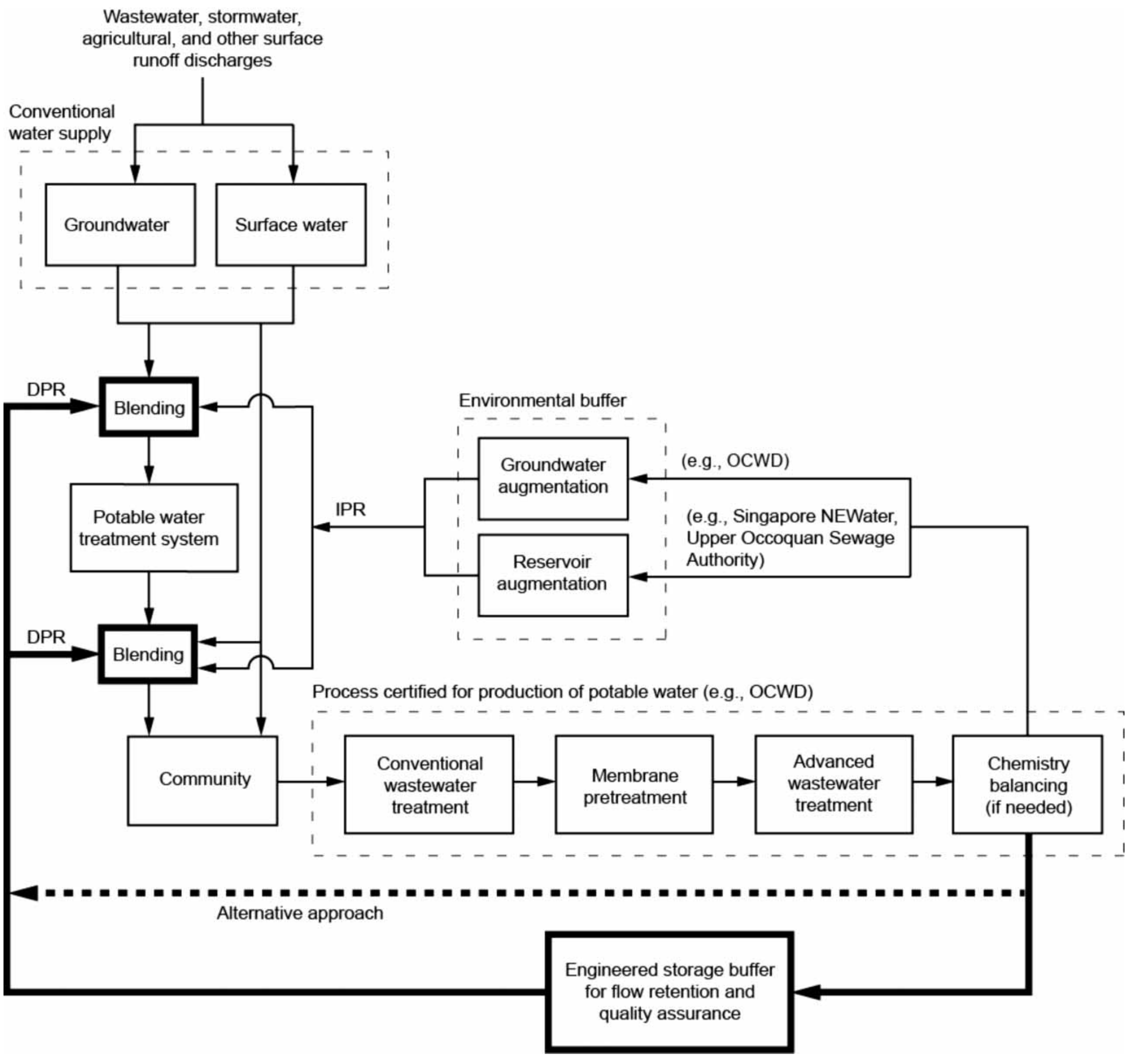

Figure 1 | Flow diagram for alternative direct potable reuse schemes (Tchobanoglous *et al*. 2011).

quality. In early IPR projects where the product water was not of the highest quality, the environmental buffer was thought to have provided a level of *in situ* advanced treatment. Further, the environmental buffer was presumed to provide loss of water identity and a measure of safety, in that it provided time to correct issues in the event that off-spec product water was detected.

However, when water is treated to a high level of purity, placement into an environmental system may not result in improved water quality, and can instead expose the purified water to potential environmental contaminants. Thus, when purified water can be produced using a system with proven performance and reliability and the quality can be validated rapidly with extensive monitoring systems, a relatively small ESB, if any, may be sufficient for use prior to blending into the potable water system.

An additional implication of the ESB concept is that, with some additional infrastructure, an existing IPR system could blend the purified product water directly with the area's general water supply system, allowing for greater flexibility in system operation. For example, when there are periods of purified water production in excess of the immediate potable demand, purified water could be placed into long-term environmental storage, such as aquifer recharge. Additional discussion on ESBs is presented in the 'Technical issues' section of this paper.

Water is water

Understandably, DPR may be the most difficult category of water reuse applications for the community to accept. One of the dilemmas in considering DPR has been the perception, even among water professionals, that nearly any water obtained from the environment, i.e., natural, is pure and better (Lohman 1988). However, the distinction that natural water is pure and better is no longer valid in many areas, mostly due to intentional and unintentional discharges of wastewater and agricultural and urban runoff. As a result, much of the research that originally addressed potable reuse has become of equal relevance to drinking water supplies taken from most water bodies. Thus, the sage words of Dr Lucas van Vuuren have successfully withstood the test of time over 40 years: 'Water should not be judged by its history, but by its quality' (Haarhoff & van der Merwe 1996).

A future imperative

It is inevitable that purified water will be used as a source of potable water supply in the future. Implementation of DPR will require a confidence in, and reliance on, the applied technology to always produce water that is safe and acceptable to consume. Designing interconnected water supply, collection, treatment, purification, and distribution systems has the benefit of providing maximum flexibility in the event of expected or unexpected shortages of natural water supply. Once a decision has been made to augment an existing water supply with purified water, the technical and implementation issues introduced in this paper must be considered. Further, the concepts described in this paper can also be applied in developing countries when provisions are made for reliable power supply and operation and maintenance for their vital water supplies.

RATIONALE FOR DIRECT POTABLE REUSE

In the past, it has been standard practice that whenever additional sources of water supply are necessary but not readily available, nonpotable water reuse options have been explored using recycled water. For example, nonpotable water reuse applications, such as agricultural and landscape irrigation, are major options for planned reuse. As a result of the preference for nonpotable reuse, water reuse applications in the United States, in order of descending water volume, are: (1) agricultural irrigation; (2) industrial recycling and reuse; (3) landscape irrigation; (4) groundwater recharge; (5) recreational and environmental uses; (6) nonpotable urban uses; and finally, (7) potable reuse (Asano 1991; Asano *et al.* 2007). However, most of the economically viable nonpotable reuse opportunities have been exploited. For example, the typical cost for parallel distribution of tertiary-treated recycled water is 0.3 to $1.7/m^3 whereas the typical cost for purified water, which could be added directly to the distribution system, is 0.6 to $1.0/m^3 (Tchobanoglous *et al.* 2011).

Indirect planned and unplanned potable reuse

Planned IPR includes groundwater recharge operations, such as Orange County Water District in California and the Occoquan Reservoir in northern Virginia (Asano *et al.* 2007). Planned IPR will continue to be of great importance in supplementing water supplies in the United States and elsewhere in the world. *Unplanned* IPR, in the cities and towns along the Colorado River as an example, occurs when treated wastewater is discharged to surface and groundwater that is subsequently used for municipal water supply. Thus, much of the research that originally addressed potable reuse is becoming of equal relevance to drinking water supplies taken from water bodies used for discharge of wastewater and runoff.

Factors limiting nonpotable and indirect potable water reuse

While there has been a clear preference for nonpotable and IPR applications, a number of factors are making it less feasible to further increase water reuse in these applications. Important limiting factors for agricultural and landscape irrigation, and IPR are listed in Table 1. Although agricultural irrigation is currently the largest user of recycled water, it is expected that this will change with the world-wide trend towards urbanization, especially near coastal areas. For example, the City of Los Angeles currently discharges about 1.5 Mm^3/d (400 Mgal/d) of treated wastewater to the Pacific

Ocean. Further, the energy to provide water supply to some areas is excessive compared to the energy to purify water. For example, the energy required to provide 1,234 m^3 (1 ac-ft) to an Orange County water system is: ocean desalination = 3,700 kWh (kilowatt-hour); State Project water = 3,500 kWh; Colorado River water = 2,500 kWh; purified water = 800 to 1,500 kWh (Tchobanoglous *et al*. 2011).

Factors favoring direct potable reuse

In addition to the limiting factors identified in Table 1, there are a number of factors that support the implementation of DPR in the future. For example, drought events are expected to become more extreme due to climate change and the potential use of purified water for potable supply offers improved overall water supply reliability in coastal metropolitan areas. Another consideration is that as the reality of unplanned IPR and concern about the quality of existing water supplies becomes more transparent and understandable to the public, there will be increased pressure to provide water of the highest quality for public consumption. Advances in treatment technology over the last decade have made it possible to produce high quality purified water with advanced water treatment processes. Additional considerations that support DPR are summarized in Table 2. Given the factors presented in Tables 1 and 2, it is clear that there is a need in some regions to consider alternatives to conventional water supply and nonpotable water reuse applications.

REVIEW OF DPR SYSTEMS

Some DPR systems that are currently in operation and/or under construction are highlighted in this section. These example projects are important because 'the treatment process flow diagrams and treatment technologies employed have been accepted by various regulatory authorities as being able to produce safe potable drinking water, and … the implementation of these projects has been accepted by the public' (Tchobanoglous *et al*. 2011). Therefore, the focus of this section is primarily on treatment technologies and not the removal of specific constituents.

Typical flow diagrams for DPR

Representative treatment process flow diagrams from (1) Windhoek, Namibia; (2) Big Springs, Texas; (3) Cloudcroft, New Mexico; and (4) Orange County Water District (OCWD) Groundwater Replenishment System (GWRS), Fountain Valley, California for potable reuse are presented on Figure 2. The Windhoek, Namibia DPR facility, shown

Table 1 | Factors that have limited nonpotable and indirect potable reuse

Agricultural irrigation

- The long distance between the municipal recycled water supplies and the major agricultural demand areas.
- The cost and disruption to construct pipe systems to convey recycled water.
- The need to provide winter recycled water storage facilities further limits agricultural reuse.
- Historically, the value of water from surface and groundwater supply sources has not reflected the true costs of providing the supply, resulting in a distinct economic disadvantage for the production of recycled water.

Urban landscape irrigation

- Landscape irrigation may not be economically feasible due to the dispersed nature of the demand.
- The cost of providing parallel distribution of recycled water supply is high due to the fact that the distance between large users in most communities is great. Further, most of the water is consumed by small users that cannot be served efficiently and or economically.

Indirect potable reuse (IPR) projects

- Communities that lack suitable hydrogeology for groundwater recharge may not be able to implement IPR projects.
- For surface water augmentation, blending and residence time requirements may limit IPR applications to large reservoirs (which are not available to many communities).

Table 2 | Factors that favor direct potable reuse

- Need for a separate recycled water distribution system is avoided.
- Alternative sources of water supply are often either of poor quality or prohibitively expensive.
- Traditional sources of surface water and groundwater supply are being limited.
- With advanced treatment technology it is now possible to remove contaminants effectively and reliably to extremely low levels that have no known health concerns.
- Purified water is a reliable source of supply which exists in close proximity to the demand.
- Communities that lack suitable hydrogeology for groundwater recharge cannot implement IPR projects.
- DPR with purified water is potentially less costly than the use of tertiary-treated recycled water for irrigation.
- DPR may require less energy than is required for other water supply sources.
- DPR avoids potential water quality issues associated with groundwater and surface water sources.
- Current technology is sufficient to replace the environmental buffer with an engineered storage buffer through a combination of monitoring, storage, and treatment reliability measures.

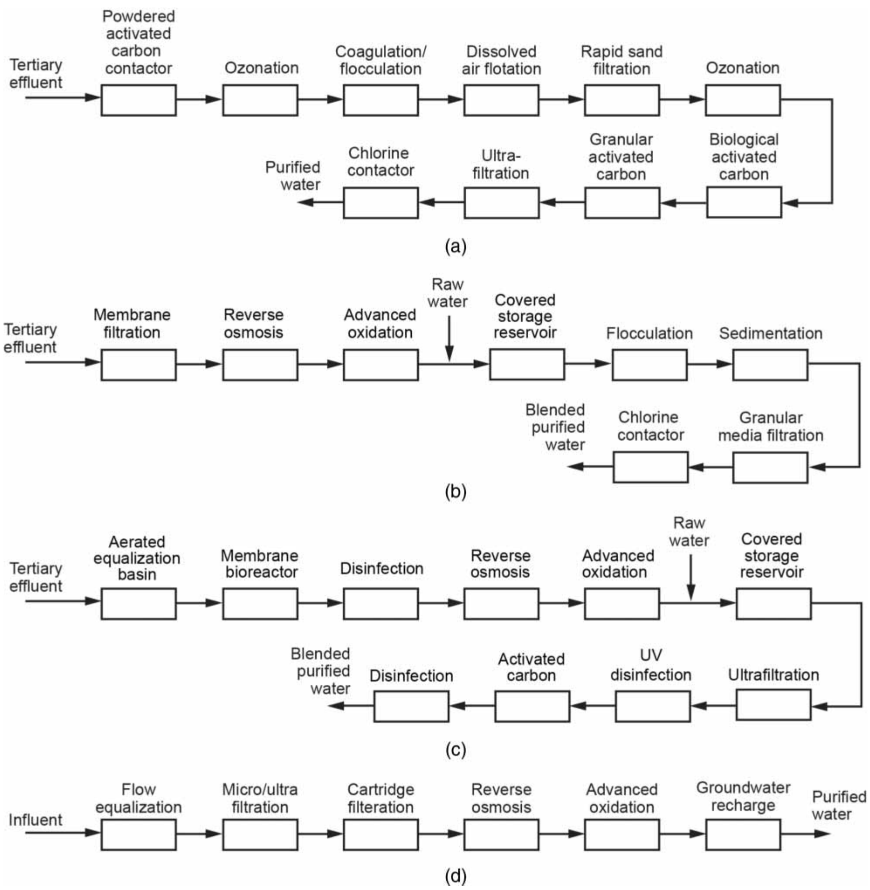

Figure 2 | Representative treatment process flow diagrams for potable reuse: (a) Windhoek, Namibia; (b) Big Springs, Texas; (c) Cloudcroft, New Mexico; and (d) Orange County Water District (OCWD) Groundwater Replenishment System (GWRS), Fountain Valley, California.

on Figure 2(a), has been in operation since 1997 and replaced the previous treatment facility, which had been in operation since 1968. It should be noted that all of the flow diagrams in Figure 2, with the exception of Figure 2(d), are consistent with the generalized conceptual DPR flow diagram given on Figure 1. Although the purified water from the GWRS system, shown on Figure 2(d), is used for groundwater recharge, the treatment process flow diagram is included as a benchmark for water quality, as the water has been determined to be safe for direct potable reuse (Burris 2010).

Assessment of flow diagrams for DPR

In reviewing the flow diagrams presented in Figure 2, it is interesting to note that a number of different unit processes have been employed for the removal of the constituents of concern in wastewater. For the near future, it is anticipated that the treatment processes employed in these flow diagrams will serve as a benchmark for the development of alternative process flow diagrams for DPR. As new treatment process flow diagrams are developed it will be important to assess the need for and size of the ESB, based on system reliability and the use of appropriate monitoring equipment and analytical techniques.

TECHNICAL ISSUES IN DPR

The technology required for advanced wastewater treatment, capable of producing an effluent of sufficient quality that is suitable for potable reuse, has been a reality for more than 40 years. However, over the last decade, the ability to produce purified water reliably from tertiary and advanced effluent at the municipal scale has become technically and economically feasible. As more communities and water agencies begin to explore the feasibility of DPR, some of the technical issues that must be addressed include appropriate treatment process configurations, features of ESBs, process reliability, and monitoring requirements. These topics are considered below along with some research needs.

Treatment process configurations for purified water production

The combination of improved technology and analytical capabilities has made it possible to validate the concept that water can be purified using several alternative process flow schemes. The basic system used to purify water consists of several processes collectively referred to as advanced treatment. The current advanced treatment scheme has evolved over time, and now commonly includes microfiltration, reverse osmosis, and advanced oxidation, as shown on the flow diagrams presented in Figure 2. Major innovations in the future are expected to include improvements in overall process cost and efficiency, such as demineralization processes that minimize brine formation and operate with reduced energy input.

Features of ESBs

ESB designs can be stand-alone facilities or incorporated into the transport and distribution system, depending on site-specific factors and needs. Stand-alone storage buffers may take a variety of forms varying from well-defined engineering structures to natural or constructed confined groundwater aquifers. The specific design of the ESB will be a function of several factors, including: (1) site-specific constraints; (2) capabilities of the monitoring and constituent detection system; (3) flow rate and degree of flow equalization required; and (4) safety factors. Important features of the ESB include:

- 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-characterized and optimized hydraulics, and
- high level of security.

In general, the storage requirements will be controlled by the time required for constituent analysis and overall reliability of the monitoring system. Purified water must be retained in the ESB for sufficient time to validate the quality of the water for specified constituents and surrogate measures prior to blending into a potable water supply for consumption.

Measures to enhance reliability

The pretreatment processes used for production of the feed water to advanced treatment and purification processes must be refined to achieve the highest level of reliability possible. Optimizations of existing processes as well as incorporation of new facilities, such as full flow equalization, are needed to produce a consistent and stable input. Measures that can be taken to enhance the reliability of a DPR system include:

- enhanced source control,
- enhanced fine screening,
- elimination of untreated return flows,
- flow equalization,
- operational mode for biological treatment,
- improved performance monitoring,
- ongoing pilot testing and
- reformulation of consumer products for improved biodegradability.

The discharge of substances known to be difficult to treat can be reduced or eliminated with enhanced source control programs. Enhanced fine screening improves the performance of biological treatment processes. The elimination of return flows is significant with respect to achieving effective nitrogen removal. Flow equalization, coupled with operational mode of the biological treatment process, is effective in the treatment of trace organics. Improved process monitoring will enhance overall process performance. Pilot testing is used to keep abreast of the latest technological developments. Elimination of consumer products that end up in wastewater that are not amenable to treatment is the long-term goal.

Monitoring and constituent detection

While there have been a number of recent improvements in online monitoring and constituent detection, it is not, at present, feasible to provide real-time monitoring of all constituents of concern. However, the identification of surrogate and indicator constituents that can be used to assess performance reliability of key unit processes can be used in place of direct measurements for all constituents of interest. The use of indicators and surrogates is somewhat site specific and will need to be established for individual treatment operations (Drewes *et al*. 2010). However, after these parameters are established they can be used to enhance the monitoring program through rapid detection programs. The ability to detect constituents of concern rapidly will reduce the overall size of the ESB facilities that are used for quality assurance.

Monitoring at specific locations is used: (1) to assess process performance and reliability; (2) for process control; and (3) to verify compliance with public health or other regulatory requirements. As described previously, the ESB is a key monitoring location because it may be the final safeguard prior to distribution in the potable water system. Thus, the development of the monitoring program needs to be planned carefully to ensure that all constituents of importance can be assessed in the product water with sufficient speed and accuracy to justify the size and design of the ESB facilities. It is at this point that off-spec water would be diverted to an alternate location, such as the wastewater treatment facility or a specified point in the purification process.

Research needs

Although the technical feasibility of DPR is well established and will only improve in the future, areas of technical research that will enhance and hasten the adoption of DPR include (1) development of sizing criteria for ESBs; (2) treatment train reliability; (3) blending requirements; (4) enhanced monitoring techniques and methods; and (5) effectiveness of equivalent advanced treatment trains. Research on public acceptance will also be an important adjunct to and will be complementary to the technical areas of research discussed in this paper.

FUTURE TECHNICAL DEVELOPMENTS

Future technical developments that will impact DPR include the need for enhanced wastewater treatment, the development of alternative treatment processes, and integrated wastewater treatment plant design for DPR.

Enhanced wastewater treatment

It is important to consider that all water discharged to the surface and groundwater, from point and non-point sources, is basically a form of IPR. In recent surveys of

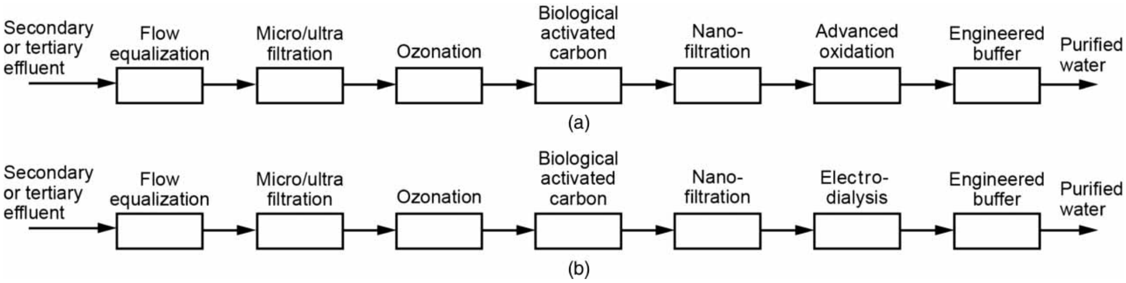

Figure 3 | Alternative advanced treatment flow diagrams with trace organic removal by (a) ozonation, biological activated carbon, nanofiltration, and advanced oxidation and (b) ozonation, biological activated carbon, nanofiltration, and electrodialysis.

surface and groundwater quality by the US Geological Survey (Kolpin *et al*. 2002; Barnes *et al*. 2008), it was concluded that essentially all surface and groundwater are contaminated with chemicals commonly associated with wastewater, such as pharmaceuticals. In the future, it is anticipated that surface and groundwater discharges will need to comply with much more stringent discharge requirements to protect sensitive environmental species and ecosystems. The level of treatment needed to protect environmental species and ecosystems may, in some cases, be higher than that needed for DPR. Thus, the implementation of DPR may make more sense environmentally than the discharge of purified water to the aquatic environment.

Alternative treatment processes for direct potable reuse

One of the major problems with most common DPR treatment schemes employing reverse osmosis is the management of brine, especially in inland locations. To deal with this issue, a variety of new advanced treatment processes are currently under development for the oxidation of trace organics, without the removal of dissolved solids. An example of such a system is shown on Figure 3(a). Another issue with DPR schemes employing reverse osmosis is the high energy usage required for treatment. An alternative treatment approach involves the use of electrodialysis as illustrated on Figure 3(b). New and enhanced biological treatment systems are also under development. As new technologies become available in the future, it is anticipated that constituent removal effectiveness will improve with a concomitant reduction in energy and resource usage.

Integrated DPR treatment designs

The current trend in water and wastewater systems design can best be described as incrementalism. In examining the treatment process flow diagrams for DPR presented previously in Figures 2 and 3, it can be concluded that the production of purified water for DPR was an afterthought. Basically additional unit processes were tacked on to the end of existing secondary treatment process flow diagrams to remove specific compounds. However, at some point in the future there will need to be a complete rethinking of urban infrastructure to obtain the highest levels of performance and reliability. For water and wastewater systems, the advanced infrastructure model will likely include decentralization, remote management, resource recovery, source separated waste streams, and application of specific optimization of water quality. What is needed is the development of integrated water management systems in which new wastewater treatment plants are planned and designed from the ground up to optimize treatment performance with respect to the production of purified water, along with the recovery of energy and resources.

SUMMARY

Because it is inevitable that DPR will become part of the water management portfolio for the reasons cited in this paper, it is important that water agencies begin to develop the necessary information that will allow DPR to become a reality. The technical feasibility of DPR is well established and will only get better in the future. In planning for wastewater treatment upgrades or new plants that will be used to produce purified water, it is imperative that the incrementalism of the past be replaced with new integrated designs that will produce purified water along with the recovery of energy and resources.

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