FRAMEWORK FOR DIRECT POTABLE REUSE

WateReuse

American Water Works Association

Water Environment Federation
the water quality people

NWRI National Water Research Institute

What Is Direct Potable Reuse?

Adapted from the Water Environment & Reuse Foundation report *Framework for Direct Potable Reuse*

Planned potable reuse involves the treatment of a community's wastewater with the express purpose of converting it into a source of drinking water. Two forms of planned potable reuse occur: direct potable reuse (DPR) and indirect potable reuse (IPR). Municipalities, utilities, and agencies interested in potable reuse will need to understand the following topics addressed.

- What is DPR?
- What is IPR?
- What is required to allow treated wastewater to be considered a new raw water source?
- What example DPR projects are available?
- What does DPR cost?
- What are the energy requirements of DPR?
- What are the comparative issues with other water sources and measures?

1.1 Direct Potable Reuse

There are two forms of DPR in use today: one involves advanced treated water (ATW), and the other involves finished water. Both forms are illustrated in Figure 1.1, as follows:

- In Figure 1.1(a), ATW is introduced with or without the use of an engineered storage buffer (ESB) into the raw water supply immediately upstream of a drinking water treatment facility (DWTF). To date, permitted operational DPR projects in the United States involve this form of DPR.

- In Figure 1.1(b), finished water is directly introduced—with or without the use of an ESB—into a drinking water supply distribution system, either downstream of a DWTF or within the distribution system. A finished water DPR project has been in operation at Windhoek, Namibia, since 1967.

Further details about the differences in these forms of DPR, including treatment trains with and without ESBs, are provided in Sections 1.1.1 to 1.1.4.

1.1.1 Introduction of Advanced Treated Water Upstream of a Drinking Water Treatment Facility

When introduced upstream of a DWTF [see Figure 1.1(a)], ATW becomes essentially another source of raw potable water. ATW typically meets all drinking water standards and regulations; however, it cannot be introduced directly into the distribution system as finished water if it was not produced in a facility permitted as a DWTF.

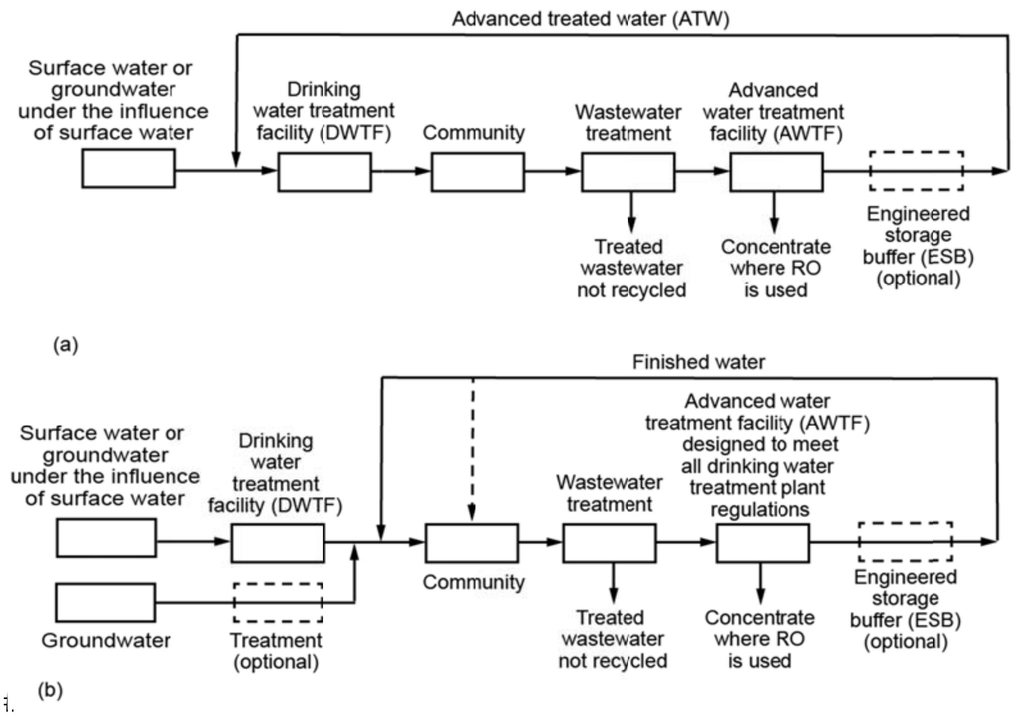

Figure 1.1. Flow diagrams for DPR: (a) with ATW introduced upstream of a DWTF; and (b) finished water introduced into the drinking water supply distribution system downstream of a DWTF.

When ATW is introduced upstream of a DWTF, the DWTF serves as an additional treatment barrier to provide an added factor of safety. In some cases, it may be necessary to use the disinfection credit available for water treatment per the Surface Water Treatment Rule (SWTR) of the Safe Drinking Water Act (SDWA) to meet required microbial log reduction objectives for DPR.

1.1.2 Treatment Train with an Engineered Storage Buffer

An engineered storage buffer (ESB), shown as a dashed box in Figure 1.1(a), may be used before the ATW is introduced upstream of a DWTF. If used, the purpose of the ESB is to provide a water storage containment facility of sufficient volumetric capacity to retain ATW for a specified time period (Tchobanoglous et al., 2011).

To ensure that the quality of the ATW meets all applicable water quality-related public health standards or quality measures prior to being introduced into a DWTF, the amount of time required to hold the ATW in the ESB should be sufficient to allow for flow continuity and the measurement and reporting of specific constituents. This definition does not mean that all regulatory standards must be monitored in the ESB prior to the release of the ATW; rather, it provides an opportunity to monitor for select key performance parameters. The use of an ESB is critical when the advanced water treatment facility (AWTF) does not have (1) redundancy or critical treatment processes that are monitored routinely (e.g., daily) and (2) online metering that can be used to monitor treatment performance accurately.

1.1.3 Treatment Train without an Engineered Storage Buffer

When an ESB is not used, as represented by the dashed box in Figure 1.1(a), the AWTF should have the following: (1) redundant treatment to allow for the continuous production (or retreatment or discharge) of ATW if one of the major treatment processes is out of specification; and (2) effective monitoring to demonstrate sufficient treatment protective of public health.

1.1.4 Direct Introduction of Finished Water into the Drinking Water Supply Distribution System

Finished water, produced in an AWTF that is also permitted as a DWTF (i.e., a facility that meets all federal, state, and local regulations), is introduced directly into the drinking water distribution system, as shown in Figure 1.1(b). The drinking water in the distribution system can be (1) treated surface water or (2) treated or untreated groundwater, which may or may not be disinfected. At this time, questions remain about the issues associated with blending different drinking waters and finished water, as well as the blending location.

The rationale for the use of an ESB with finished water is the same as that for ATW, as discussed in Section 1.1.2. Bypassing the DWTF could be done only with appropriate monitoring and response time procedures. In the future, as monitoring technologies become more sensitive for the measurement of critical constituents of concern (COCs), it is likely that the DWTF will be bypassed, assuming all public health and monitoring requirements are being met and the AWTF is also permitted as a DWTF. Because of the many unknowns associated with the management of finished water, this form of DPR will require additional studies to demonstrate the feasibility and safety of the practice; therefore, it is not the focus of this framework document.

1.2 Indirect Potable Reuse

In an IPR process, ATW or tertiary effluent is introduced into an environmental buffer before being withdrawn for potable purposes. The purpose of the environmental buffer is to provide storage, transport, and, in some cases, an additional barrier for the protection of public health; however, the environmental storage of highly treated water, if not stabilized or mixed with other water, can also add contaminants and degrade the water (e.g., dissolution of metals from the groundwater aquifer or microbial and other contaminants in surface impoundments).

In Figure 1.2(a), the environmental buffer is a groundwater aquifer. ATW can be applied by spreading or direct injection, whereas tertiary effluent is applied by spreading to take advantage of soil aquifer treatment. Planned IPR through the recharge of groundwater aquifers has been practiced in California since 1962 (Crook, 2010).

In Figure 1.2(b), a surface water reservoir or other water body serves as the environmental buffer. Planned augmentation of a surface water source with treated wastewater has been practiced in Fairfax County, VA, since 1978 (UOSA, no date). It is also important to note that when the volume of the reservoir or other water body does not meet required dilution and storage requirements, the proposed IPR project [see Figure 1.2(b)] becomes a DPR project [see Figure 1.1(a)].

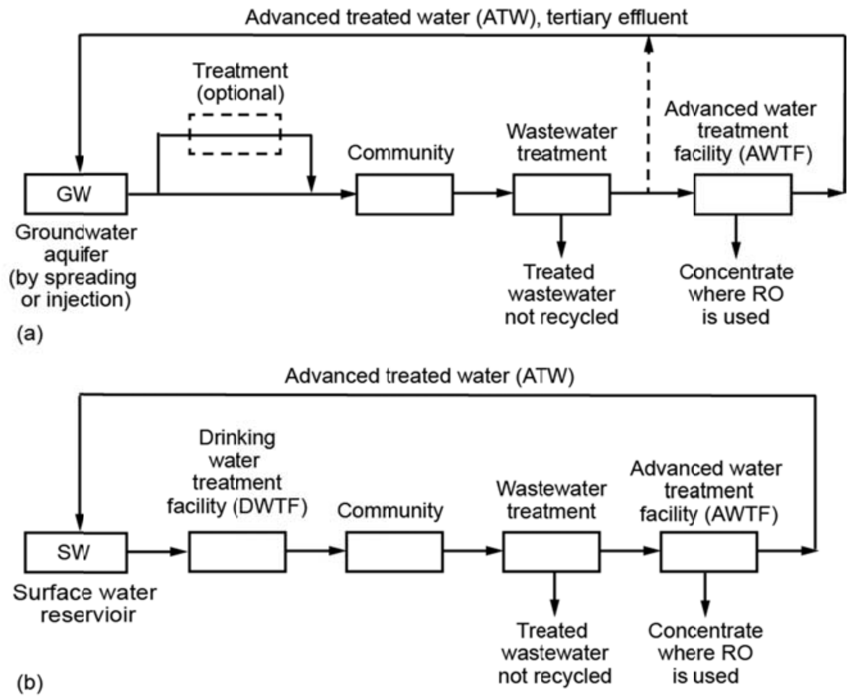

Figure 1.2. Flow diagrams for IPR: (a) with a groundwater aquifer as an environmental buffer; and (b) with a surface water reservoir as an environmental buffer.

1.3 New Raw Potable Water Source (Advanced Treated Water)

Treatment technologies capable of producing ATW that meets all drinking water standards have been demonstrated in numerous investigations and AWTFs. In general, where reverse osmosis (RO) is used, the ATW is of higher quality than most conventional treated drinking waters with respect to total organic carbon (TOC) and total dissolved solids (TDS), as well as trace contaminants; however, regulators, public health professionals, and practitioners have not reached consensus as to the appropriate framework and governing parameters for potable reuse.

Recognizing that there may be potential issues that require careful examination, it is reasonable to propose consideration of ATW as a source for drinking water supply along with surface water and groundwater.

1.4 Examples of Direct Potable Reuse Projects

Three examples of DPR projects currently in operation or under design/construction are reviewed briefly in Table 1.1.

Notably, the treatment process flow diagrams and treatment technologies used for these projects have been accepted by various regulatory authorities as being able to reliably produce a safe drinking water source. Furthermore, the DPR projects presented in Table 1.1 have been accepted by the public.

Table 1.1. Examples of DPR Projects

Entity	Description
Wichita Falls, TX (emergency water supply)	Chlorinated secondary effluent is treated with MF, RO, and UV disinfection, and then blended 50/50 with other raw water supplies (see Figure 1.1a) before being treated at the city's DWTF. The project began operation in July 2014 and was implemented on an emergency basis in response to severe drought conditions. The MF/RO advanced treatment system was installed originally to treat a brackish surface water source and will be converted back to this use in the future (Nix, 2015). Following significant rainfall events in 2015, the facility has been taken offline.
Colorado River Municipal Water District Raw Water Production Facility, Big Spring, TX	Filtered secondary effluent is treated with MF, RO, and UV-AOP. The treated water is blended with raw water in a transmission line (see Figure 1.1a). The blended water is then treated in one of several DWTFs before distribution. The DPR process has been operational since spring 2013 (Livingston and Salveson, 2008; Salveson et al., 2015).
Windhoek, Namibia	Starting in 1968, reclaimed water was added to the drinking water supply system. The plant was upgraded in 1997, and the blending of finished water (without RO treatment) with other drinking water occurs directly in the pipeline that feeds the drinking water distribution network (see dashed line in Figure 1.1b; du Pisani, 2005; Lahnsteiner and Lempert, 2005).

Notes: AOP=advanced oxidation process; DPR=direct potable reuse; DWTF=drinking water treatment facility; MF=microfiltration; RO=reverse osmosis; UV=ultraviolet.

Source: Adapted from Raucher and Tchobanoglous (2014).

1.5 Cost of Direct Potable Reuse

Cost is an important consideration in evaluating new water supply alternatives, especially for DPR projects. In many cases, the costs of DPR compare favorably with the costs of other new sources of water. The cost for DPR is made up of the costs of the following elements:

- Advanced water treatment.
- ESB (if used).
- Residuals management.
- Concentrate management when RO is employed as part of the treatment train.
- Conveyance.

Comparative unit costs for DPR and other water supply options are presented in Table 1.2 and discussed in Sections 1.5.1 to 1.5.5. The unit costs include both annualized capital costs and operation and maintenance (O&M) costs. The reported unit cost ranges reflect site-specific conditions, different plant capacities, and the use of different economic criteria for the calculation of annualized capital cost.

Table 1.2. Comparative Unit Costs of Advanced Treated Water, Brackish and Seawater Desalination, and Conservation Measures

Supply Option	Cost $\$/10^3$ gal (\$/AF)[a]			
	Treatment	Residuals Management	Concentrate Management[b]	Conveyance and Blending Facilities[b]
AWTF with RO	2.10–2.76 (685[c]–900)	0.03–0.15 (10–50)	0.21–2.38 (70–775)[d]	0.31–3.07 (100–1000)
AWTF without RO	1.23–2.15 (400–700)	0.03–0.15 (10–50)	Not applicable	0.31–3.07 (100–1000)
Brackish groundwater desalination (inland)	1.23–2.45 (400–800)	0.02–0.06 (5–20)	0.21–2.38 (70–775)[d]	0.31–3.07 (100–1000)
Seawater desalination	5.98–10.74 (1950–3500)	0.06–0.31 (20–100)	0.21–0.61 (70–200)	1.23–9.21 (100–3000)
Retail cost of treated imported surface water	1.23–3.99 (400–1300)		Not applicable	0.31–1.84 (100–600)
Water use efficiency, conservation, and use restrictions	1.38–2.92 (450–950)			Not applicable

Notes: [a]The reported costs are based on an Engineering News Record Construction Cost Index of 9900 (value of index in 1913=100). [b]The costs for RO concentrate or brine management and conveyance are site specific and will vary widely. [c]Based on actual costs from OCWD for the original AWTF. The estimated cost for the new plant expansion, including influent flow equalization, is $\$2.15/10^3$ gal (\$701/AF; see Table 1.3 and Figure 1.3). $(\$/10^3\text{ gal}) \times 325.892 = \$/\text{AF}$; $(\$/10^3\text{ gal}) \times 0.264 = \$/\text{m}^3$. AWTF=advanced water treatment facility; RO=reverse osmosis.

Source: Adapted in part from Raucher and Tchobanoglous (2014).

1.5.1 Cost of Treatment

As reported in Table 1.2, the treatment costs for the production of ATW are based on actual and projected costs for an AWTF with a capacity of 5 Mgal/d or greater. Treatment costs for smaller facilities are difficult to estimate because they are site specific, and economies of scale generally do not apply.

The lowest cost of \$685/ AF ($\$2.1/10^3$ gal) for ATW, as footnoted in Table 1.2, is based on the actual unsubsidized cost of the original 70 Mgal/d AWTF for the Groundwater Replenishment System (GWRS), an IPR project operated continuously since January 2008 by the Orange County Water District (OCWD). An additional 30 Mgal/d of capacity came online in June 2015. The treatment technologies employed for the production of ATW at the original and expanded facilities at OCWD are reported in Table 1.3 and illustrated in Figure 1.3.

Table 1.3. Summary of Treatment Technologies Employed for the Production of ATW at OCWD

Treatment Technology	OCWD Original[a]	OCWD Expansion[b]
Filter screens	✔	✔
Influent flow equalization		✔
Microfiltration	✔	✔
Cartridge filtration	✔	✔
Reverse osmosis	✔	✔
Advanced oxidation	✔	✔
Decarbonation	✔	✔
Lime stabilization	✔	✔

Notes: [a]Capacity of the original AWTF is 70 Mgal/d of ATW.
[b]Capacity of the expansion AWTF is 30 Mgal/d of ATW.
See also Figure 1.3.

Source: Raucher and Tchobanoglous (2014).

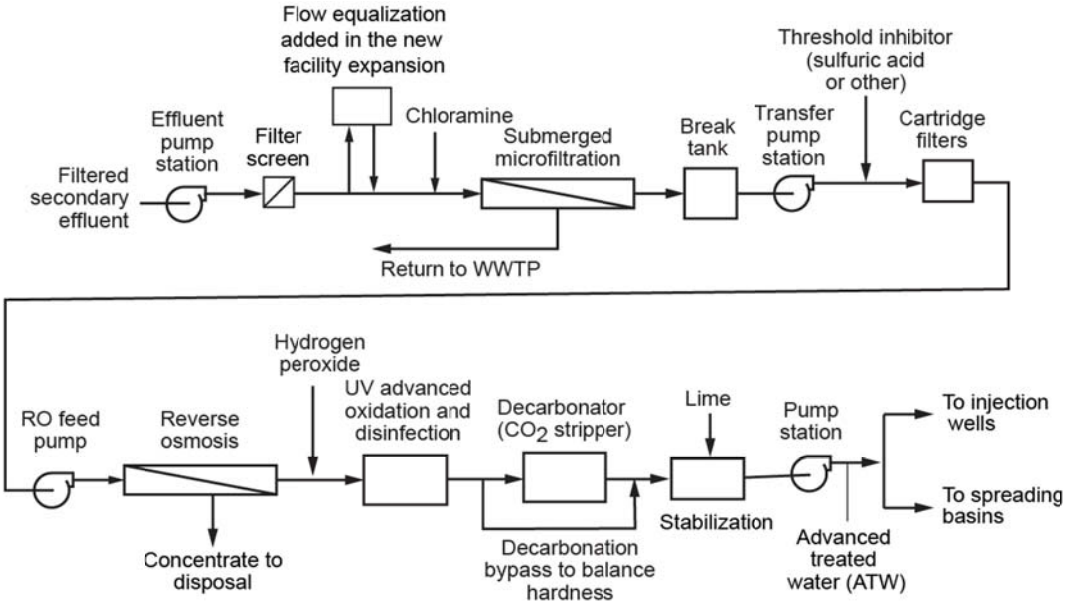

Figure 1.3. Flow diagram for the AWTF at OCWD.

Note: Flow equalization was not included in the original flow diagram, but was added when the capacity of the facility was increased from 70 to 100 Mgal/d.

Because of the successful long-term operation of the AWTF at OCWD, the combination of treatment processes employed at OCWD to produce ATW is used often as the default treatment train for potable reuse applications. It is important to note, however, that a number of agencies have conducted or are conducting studies to demonstrate that non-RO technologies may be suitable to produce ATW where RO concentrate disposal is a barrier to DPR implementation. The projected base cost of advanced water treatment for an AWTF employing RO is assumed to be the same as that for OCWD because additional treatment units will not be required and OCWD has undertaken more monitoring than will be required for future AWTFs. Projected costs for advanced water treatment without RO are also included in Table 1.2.

1.5.2 Cost of the Engineered Storage Buffer

Costs for an ESB facility also are site specific and will depend on the volumetric capacity, configuration, construction materials, fittings and accessories, and degree of instrumentation. Configurations for an ESB can include plug-flow pipelines, baffled tanks, or tanks in parallel operated in a fill, storage, and draw mode. Typical capital costs for a three-tank ESB facility with an 8 hour failure response time (FRT) can vary from $2.50/gal for a flow rate of 5 Mgal/d to $1.25/gal for a flow rate of 20 Mgal/d or greater. The corresponding unit costs, which include capitalized costs (based on a 30 year amortization period and an interest rate of 2.5%) and O&M, are estimated to be $0.26 and $0.18/10^3 gal, respectively.

1.5.3 Cost of Residuals Management

With the exception of RO concentrate, the liquid and semisolid residuals resulting from treatment usually are recycled to either the wastewater treatment plant (WWTP) or the headworks of the AWTF. The reported cost range for residual management depends on how the costs are allocated (e.g., charged against the WWTP or AWTF).

1.5.4 Cost of Reverse Osmosis Concentrate Management

The costs for RO concentrate management are site specific and vary widely depending on the characteristics and volume of concentrate that must be managed and the disposal method. The low end of the cost, $0.21/10^3 gal ($70/AF), is based on disposal by deep well injection. The high-end cost of $2.38/10^3 gal ($775/AF) is based on zero liquid discharge (ZLD) using energy-intensive processes to produce a dry product that can be disposed of in a landfill. The cost for the disposal of RO concentrate using an existing deep water ocean outfall is typically in the range of $0.35 to $0.38/10^3 gal ($115 to $125/AF).

1.5.5 Cost of Conveyance

Conveyance costs will vary with siting opportunities for AWTFs. The conveyance cost for OCWD's IPR project, in which ATW is transported by pipeline 13 miles to spreading basins, is $0.37/10^3 gal ($120/AF). Conveyance costs for some IPR projects in the planning and development stage vary from $0.31 to more than $3.07/10^3 gal ($100 to more than $1,000/AF).

1.6 Energy Requirements for Direct Potable Reuse

The energy required for DPR is made up of the energy requirements for: (1) advanced water treatment; (2) conveyance; and (3) RO concentrate management. Each of these energy requirements is considered in Sections 1.6.1 to 1.6.3.

1.6.1 Energy Requirements for the Production of Advanced Treated Water

The overall energy requirements for secondary and advanced water treatment, brackish and seawater desalination, imported water, and conventional and membrane-based water treatment are reported in Table 1.4, along with corresponding carbon footprint values.

As shown, the energy required to produce ATW will vary from 3.25 to 3.5 kWh/10^3 gal (1,050 to 1,140 kWh/AF) beyond that needed for secondary treatment, depending on the TDS in the wastewater. The lowest value for energy usage (3.25 kWh/10^3 gal) for ATW, as footnoted in Table 1.4, is based on actual operating experience at OCWD's original AWTF. By comparison, seawater desalination (with energy recovery) requires about 9.5 to 14.75 kWh/10^3 gal (3,100 to 4,810 kWh/AF). Inter-basin transfers of water often can require large expenditures of energy to pump water over the watershed divides that separate and define the basins.

The carbon footprint values associated with the energy required for various technologies and water sources are presented in Table 1.4. The carbon footprint reflects the carbon dioxide emission equivalents released in the production of a kilowatt hour of energy, which will vary by state depending on the mix of energy sources. In the United States, the baseload range across the Emissions and Generation Resource Integrated Database (eGRID) regions varies from 0.20 to 0.86 kg CO_2e/kWh; the non-baseload range is from 0.42 to 0.94 kg CO_2e/kWh. For purposes of comparison, the reported values were computed using a conversion factor of 0.50 kg CO_2e/kWh.

1.6.2 Energy Requirements for Conveyance

The energy requirements for conveyance are site specific and will depend on the total dynamic head for the conveyance system, properties of the fluid being pumped, and efficiency of the pumping equipment. The energy requirements for the support equipment and facilities must also be taken into account.

For example, for an ATW flow rate of 17.9 Mgal/d or 27.7 ft^3/s (20,000 AF/y), the energy required for conveyance for every 10 feet of total dynamic head (static head plus dynamic losses) is equal to 41.9 horsepower or 31.3 kilowatts (kW), which corresponds to 0.042 kWh/10^3 gal (13.7 kWh/AF). The computed value is based on the assumption that the specific weight of the ATW at 20°C is 62.3 lb/ft^3 and the pump efficiency is 75%. If the total dynamic head is 250 feet (which is not uncommon), then the corresponding value would be 1.05 kWh/10^3 gal (342 kWh/AF). The energy required for conveyance can clearly become significant (Raucher and Tchobanoglous, 2014).

Table 1.4. Comparative Energy Requirements for Wastewater and Water Treatment, Advanced Water Treatment, and Alternative Sources of Surface Water

Technology/Water Source	Energy Required			Carbon Footprint ($kg\ CO_{2e}/10^3$ gal)
	Range ($kWh/10^3$ gal)	Typical[a]		
		$kWh/10^3$ gal	kWh/m^3	
Secondary treatment without nutrient removal[b,c]	1.40–1.05	1.25	0.33	0.63
Tertiary treatment with nutrient removal and effluent filtration[b,c]	1.95–1.60	1.85	0.49	0.93
AWTF	4.00–3.25[d]	3.60	0.95	1.80
Brackish water desalination[e]	3.10–6.20	5.85	1.55	2.93
Ocean desalination[e]	9.50–14.75	12.00	3.17	6.00
Interbasin transfer of water, California State Water Project[f]	7.92–9.92	9.20	2.43	4.60
Interbasin transfer of water, Colorado River water[g]	6.15–7.40	6.15	1.62	3.07
Conventional water treatment[h]	0.30–0.40	0.37	0.10	0.19
Membrane-based water treatment[i]	1.00–1.50	1.25	0.33	0.63

Notes: [a]Typical energy values are for WWTPs and DWTFs with an average design flow of 10 Mgal/d. [b]Energy recovery is not included. [c]The range of energy consumption values is for a 5 and 100 Mgal/d treatment plant, respectively. [d]Based on actual operating records from OCWD for the original AWTF (see Table 1.3 and Figure 1.3). [e]Energy required for distribution is not included. [f]Energy required, including energy recovery, for delivery to the point of treatment (Southern California)—the energy required for treatment and distribution is not included, and the difference in energy values depends on the point of water delivery. [g]Energy required for delivery to the point of treatment (Southern California), not including treatment and distribution—the difference in energy values depends on the point of water delivery. [h]Raw water pumping, rapid mix, coagulation, flocculation, sedimentation, filtration, and disinfection (finished water pumping is not included). [i]Raw water pumping, rapid mix, chemical feed, dissolved air flotation, ultrafiltration, and disinfection (finished water pumping is not included). $(kWh/m^3) \times 3.785 = kWh/10^3$ gal; $(kWh/10^3$ gal$) \times 325.892 = kWh/AF$; $(kWh/10^3$ gal$) \times 0.5 = CO_{2e}/10^3$ gal. AWTF-advanced water treatment facility.

Sources: Adapted in part from Larson et al. (2007); Taffler et al.(2008); WEF (2009); Stillwell et al. (2010); EPRI (2013); and Raucher and Tchobanoglous (2014).

1.6.3 Energy Requirements for Reverse Osmosis Concentrate Management

The energy requirements for RO concentrate management are site specific and more difficult to generalize than conveyance costs. For example:

- If it is assumed that the percentage of concentrate from an RO treatment process with a product water flow of 17.9 Mgal/d or 27.7 ft^3/s (20,000 AF/y) is 15%, then the amount of concentrate that must be disposed of per year would be 3.1 Mgal/d {[(17.9 Mgal/d)/0.85] – [(17.9 Mgal/d)]} or (3,530 AF/y).
- If the weight of the RO concentrate at 20°C is 63.0 lb/ft^3, total dynamic head is 30 feet, and pump efficiency is 75%, then the energy required for discharge through an ocean outfall is about 0.127 $kWh/10^3$ gal (41.1 kWh/AF), based on product water production.

1.7 Comparative Issues with Other Water Sources and Measures to Direct Potable Reuse

When determining whether to proceed with a DPR program, it is useful to compare the issues associated with developing and implementing DPR, as discussed in this here, to the issues associated with developing and implementing alternative water sources and measures. Comparative issues are reviewed in Table 1.5 with respect to the following: (1) imported surface waters; (2) desalination; (3) IPR; (4) centralized nonpotable reuse (C-NPR); (5) decentralized nonpotable reuse (D-NPR); and (6) conservation and curtailments. The relative importance of these issues will depend on local conditions.

Table 1.5. Comparative Issues with Alternative Sources of Water and Other Water Management Measures to DPR

Imported Waters
• New sources of imported water are difficult, if not impossible, to develop. • Withdrawing water from inland areas, transporting it to population centers, treating and using it once, and discharging it to coastal waters is, in the long term, less sustainable than other options. • Imported water sources: (1) are subject to natural and institutional disruptions and limitations, resulting in potentially large interannual variability; (2) can be of variable quality (e.g., high salt load); (3) often require significant amounts of energy for transport; (4) can impose significant adverse environmental consequences when local water is extracted; (5) reduce potential environmental impacts of wastewater discharges to surface waters; and (6) are relatively expensive, the cost of which will continue to escalate in the future. • Imported water is also subject to natural and societal forces that are difficult to control, including: (1) increased demands from population growth; (2) drought; (3) changes in snowpack, rainfall, or other natural sources of replenishment; (4) seismic events; and (5) future environmental regulations, water rights determinations, and associated legal challenges. • In many locations, imported water increases local salt loading. • Extensive treatment may be required for low-quality imported water sources.

Desalination

- Ocean desalination is a technically feasible option that can provide a high-quality, potable supply after blending or chemical addition, but with a number of drawbacks, including:
    - Potential environmental impacts associated with ocean feed water intakes, brine disposal and discharges, and construction of facilities at sensitive shoreline or near-shore locations.
    - Relatively high energy demands and carbon footprints.
    - Red tides and other ocean water quality challenges.
    - Coastal facilities that may be vulnerable to sea level rise and storm surges.
- Inland brackish water desalination is less costly than ocean desalination because of much lower salt content, but has significant brine management challenges.
- Ocean desalination facilities in the United States are subject to regulatory requirements.
- Ocean desalination is more expensive than potable reuse, often by a factor of 2:1 per gallon.
- When desalinated source water is recycled, it increases the amount of water available for local beneficial use.

Indirect Potable Reuse

- An environmental buffer provides benefits such as storage, retention time, and additional treatment. It may increase public favor for IPR over DPR.
- In some locations, the lack of surface or groundwater buffers prohibits IPR, but allows DPR.
- Degradation or contamination of ATW could occur when it is released into the environmental buffer.
- Significant costs are associated with protecting, maintaining, operating, and monitoring environmental buffers.
- Water rights issues may arise when water is placed into an environmental buffer.
- De facto potable reuse occurs when downstream surface waters, subject to upstream wastewater discharges, are used as a source of drinking water.

Centralized Nonpotable Reuse (C-NPR)

- Typically, water for C-NPR applications does not need to be treated to the same level as for DPR.
- Separate distribution systems require a significant investment in pipes and pumps, and O&M (often for small amounts of recycling) is not required for IPR or DPR.
- Because many C-NPR demands are seasonal (e.g., golf course watering), water recycling assets are underused part of each year. Storage needs to be created to match year-round production with part-year demands.
- Implementing C-NPR or IPR entails some disruption and costs associated with the construction of large-scale pipeline projects.
- The potential for cross-connections always exists with dual water systems, along with the attendant costs of prevention and correction.

Decentralized Nonpotable Reuse (D-NPR)
• D-NPR includes graywater systems, rainwater capture systems, and decentralized treatment plants. • Satellite wastewater treatment plants can be used for local applications (e.g., greenbelt watering). • Even if D-NPR systems are implemented, homeowners must still pay for community water system infrastructure costs. • Unless an entire area is converted to D-NPR, the quantities of water recycled will be small compared to the potential for C-NPR, IPR, or DPR. • Based on detailed cost analyses, C-NPR is more cost effective than individual home D-NPR. • Financing will be difficult for individual home D-NPR systems. • The potential for cross-connections and less reliable maintenance always exists with separate water systems.
Conservation and Curtailments
• Significant per capita water use reductions have been realized in residential, commercial, and industrial settings through past efforts to educate water users and incentivize water savings through rebates and other mechanisms. Although additional water conservation measures will continue to reduce water demand, the cost per volume of water saved will increase steadily. • Code-required proliferation of water-saving appliances, such as low-flush toilets, has systematically contributed to lower water consumption rates in municipalities and reduced consumer water costs; however, reduced consumption may trigger higher water rates for cost recovery. • Typical costs estimated for conservation efforts are only those expenses borne by the community water utility; the costs borne directly and indirectly by customers investing in water-saving appliances or forgoing lawns and gardens are not factored into overall cost estimates.

Notes: ATW=advanced treated water; DPR=direct potable reuse; IPR=indirect potable reuse; O&M=operations and maintenance.

Source: Adapted in part from Raucher and Tchobanoglous (2014).

1.8 References

Crook, J. *Regulatory Aspects of Direct Potable Reuse in California*. National Water Research Institute: Fountain Valley, CA, 2010. http://nwri-usa.org/pdfs/NWRIPaperDirectPotableReuse2010.pdf (accessed 9/3/2015)

du Pisani, P. L. Direct Reclamation of Potable Water at Windhoek's Goreangab Reclamation Plant. In Khan, S. J.; Muston, M. H.; Schafer, A. I., eds.; *Integrated Concepts in Water Recycling.* University of Wollongong: New South Wales, Australia, 2005.

EPRI. *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries.* Electric Power Research Institute: Palo Alto, CA, 2013.

Lahnsteiner, J.; Lempert, G. Water Management in Windhoek, Namibia. In *Proceedings of the IWA Conference*, *Wastewater Reclamation & Reuse for Sustainability*, Jeju, Korea, 2005.

Larson, D.; Lee, C.; Tellinghuisen, S.; Keller, A. California's Energy–Water Nexus: Water Use in Electricity Generation. *Southwest Hydrol.* **2007,** *6* (5), 16–19.

Livingston, E.; Salveson, A. Village of Cloudcroft, New Mexico’s PUReWater Project, unpublished slide presentation given at the WaterSmart Innovations Conference and Exposition, October 8–10, 2008, in Las Vegas, NV.

Nix, D. Personal communication, Public Utilities Operations Manager, City of Wichita Falls, TX, 2015.

Raucher, R.; Tchobanoglous, G. *The Opportunity and Economics of Direct Potable Reuse*. WateReuse Research Foundation: Alexandria, VA, 2014.

Salveson, A.; Steinle-Darling, E.; Trussell, S.; Trussell, B.; McPherson, L. *Guidelines for Engineered Storage for Direct Potable Reuse*. WateReuse Research Foundation: Alexandria, VA, 2015.

Stillwell, A. S.; Hoppock, D. C.; Webber, M. E. Energy Recovery from Wastewater Treatment Plants in the United States: A Case Study of the Energy–Water Nexus. *Sustainability.* **2010,** *2*(4), 945–962.

Taffler, D.; Lesley, D.; Zelenka, A. Hidden Potential—Recycled Water and the Water–Energy–Carbon Nexus. *Water Environ. Technol.* **2008,** *20* (11), 34–41.

Tchobanoglous, G.; Leverenz, H.; Nellor, M. H.; Crook, J. *Direct Potable Reuse: A Path Forward.* WateReuse Research Foundation: Alexandria, VA, 2011.

Water Environment Federation (WEF). *Energy Conservation in Water and Wastewater Treatment Facilities*, Manual of Practice 32, WEF Press: Alexandria, VA, 2009.

UOSA. Upper Occoquan Sewage Authority, web page not dated. http://www.uosa.org/IndexUOSA.asp (accessed 9/3/2015)