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The costs of direct and indirect potable water reuse in a medium-sized arid inland community

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ABSTRACT

Planned potable water reuse can improve the reliability of water supplies by providing drinking water from wastewater. While the US government predicts near-term conflict over water in numerous small-to-medium-sized arid inland communities, knowledge gaps exist regarding the cost of potable reuse for this context, making it difficult for water managers to understand the feasibility of options. This research aims to inform decision-making about potable reuse in small-to-medium-sized arid inland communities by estimating the total present worth of several indirect and direct potable reuse treatment scenarios. We find that the present worth for indirect potable reuse that uses an aquifer as an environmental buffer is only slightly higher than for direct potable reuse that includes drinking water treatment; the present worth of both of these scenarios is higher than for direct potable reuse that does not include drinking water treatment due to the additional pumping and piping requirements. Further, scenarios including reverse osmosis for advanced treatment have significantly higher present worth values than those including ozone/biological activated carbon. All reuse scenarios considered cost far less than purchased water. Costs aside, any scenario must also be acceptable to regulators and the public and approvable from a water rights perspective.

1. Introduction

Sustainable communities must balance current development and resource use with the needs and quality of life of future generations. Critical among both current and future needs is access to adequate water supplies of acceptable quality. Communities can choose between numerous supply- and demand-side options to improve the sustainability and reliability of potable water supplies [1–3]. Indirect and direct potable reuse (IPR and DPR, respectively) are two supply-side options that hold particular promise for significantly increasing "water productivity" by recovering drinking water from purified wastewater [1]. With planned IPR, highly treated wastewater treatment plant (WWTP) effluent is held for a specified amount of time in an environmental buffer, such as an aquifer or reservoir, prior to being directed to groundwater treatment or a drinking water treatment plant (DWTP) [4]. With DPR, no environmental buffer is included, and treatment can take place either in separate WWTP and DWTP systems, or in a single advanced treatment system [4–7].

With increasing population and development pressures, it is not surprising that IPR and DPR are of increasing interest to communities with exceptional water scarcity. Numerous IPR systems exist around the world, and while IPR may reduce water contamination risk by providing dilution and additional biological and physical treatment [8], it is inefficient in that highly treated water may be degraded when directed to an environmental buffer, and therefore wastes energy and resources by treating the same water twice [7,9]. IPR has the potential to be more expensive than DPR and have a greater carbon footprint because of additional piping, pumping, and treatment; however, the cost comparison is context specific since it depends on various site factors and the location of the environmental buffer [5–7,9,10]. Far fewer DPR systems exist worldwide; while a facility in Windhoek, Namibia has been operating successfully in various configurations since 1968 [11], municipal-scale DPR is relatively new to the US. Facilities in operation or design in Texas and New Mexico (e.g., those in Big Spring, TX, and Cloudcroft, NM) have paved the way for increased awareness and discussion of DPR as a potentially reliable and economical option and have led to development of guidance and regulations for implementing DPR.

Though many of the communities that may be interested in the possibility of planned potable reuse are small-to-medium-sized and

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scattered throughout the inland Southwestern US [12], most of the research on potable reuse has focused on large coastal communities with relatively high mean household incomes [13], such as Orange County, Los Angeles, and San Diego, California. Potable reuse options may be different for larger, wealthier coastal communities as compared to smaller, less affluent inland ones − not only in terms of the technologies and process configurations that are appropriate, but also in the ability and/or willingness-to-pay for the required technologies. Costs are a significant concern because reclaimed water may be expensive relative to the artificially low water prices to which the public has grown accustomed [7]. Also, potable reuse implementation, especially DPR, involves operation and maintenance of a high-tech treatment system, which requires technical expertise that some smaller communities may lack [14].

2. Project objectives and overview

2.1. Project objectives

This paper aims to contribute to the scant literature on potable reuse in small-to-medium-sized arid inland communities by developing an estimate of the costs of potable reuse options and identifying constraints that must be addressed when considering implementation of future reuse projects. Experts have suggested that numerous communities and local contexts be studied for a broader understanding of water management alternatives [15], and there is little research on planned potable reuse in New Mexico, despite the DoI's prediction that water conflict in the state's urban centers will be "highly likely" by 2025 [12]. Bernalillo County, NM, was selected as a case study for this research because it possesses a set of characteristics that is different from previous case studies found in the literature: (1) it is a medium-sized inland community with significant potential for water conflict [12]; (2) the population is highly diverse with a relatively low mean household income [13]; and (3) the location presents technical challenges not found in coastal areas. The focus was on the Albuquerque-Bernalillo County Water Utility Authority (ABCWUA), which is the largest water utility in NM and provides water supply and wastewater collection and treatment for over 500,000 people [16]. Managers at the ABCWUA expect that IPR and/or DPR may become parts of the potable water portfolio within approximately a decade.

Since most IPR and DPR research has focused on large coastal communities, knowledge gaps exist regarding the costs associated with planned potable reuse technologies and treatment process configurations that are appropriate for an arid, inland context. As a result, some public utilities in arid, inland communities are struggling with long-term planning and selection of appropriate strategies to mitigate shrinking water supplies while minimizing constraints to sustainable community planning. Research is needed to better understand which potable reuse options are optimal for arid, inland communities, including an examination of how these options' costs compare. The focus of this study is on the IPR and DPR treatment schemes appropriate for the inland context and their costs as reported in the peer-reviewed and grey literature; the treatment schemes included were not modeled or otherwise evaluated to understand or comment on the differences among them in produced water quality. The results of this study will be useful to Bernalillo County and the ABCWUA as well as other mid-sized inland communities throughout the arid Southwest. Our intent is that water planners and policymakers in arid inland communities can use the study results to help them consider the costs and constraints of various potable reuse options. Ideally, in addition to costs, they would have access to a decision tool that would aid in evaluating various water resource development strategies, given climate and demographic uncertainties [17]. However, knowledge of the estimated costs of different options will provide a starting point for planning and evaluating the feasibility of reuse.

2.2. Project overview and scenarios considered

Advanced treatment process configurations for potable reuse facilities usually include reverse osmosis (RO), although the technology has three major drawbacks: (1) high energy requirements, (2) the environmental challenge of concentrate disposal [18], and (3) a loss of approximately 15–20% of the feed water, an important limitation in communities facing serious water shortages. Coastal communities can dispose of concentrate into the sea [7], but inland communities must find alternative disposal options. It is reasonable for inland communities to consider advanced treatment options that do not include RO [6] in order to avoid the technology's drawbacks [7,45], in part because it is possible that these drawbacks may result in higher costs that are unaffordable to smaller communities, as will be discussed later in this paper.

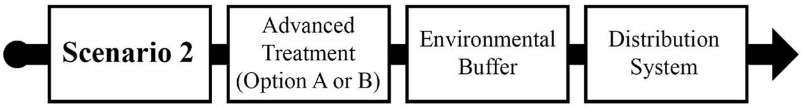
For example, inland communities could consider an advanced treatment train for potable reuse that includes ozone plus biofiltration or biological activated carbon (O_3/BAC) as an alternative to one that includes RO; the full treatment train might look something like O_3/BAC followed by ultraviolet (UV) disinfection, granular activated carbon, UV and an advanced oxidation process (AOP), similar to what has been discussed in the literature [7]. Such a train would likely use less energy and would avoid creation of a waste concentrate stream [19].[1] O_3/BAC is less expensive than RO because of the reduced energy requirements, elimination of concentrate and waste management costs, and nearly 100% feed water recovery, although the actual present worth cost difference has yet to be reported in the peer-reviewed literature.

Several scenarios to increase the potable water supply were considered in this study; these scenarios complement those considered by Raucher and Tchobanoglous [20]. The scenarios considered were inland IPR and DPR, as discussed by Tchobanoglous et al. [6], and the purchase of water rights. *Scenario 1* represents the municipal purchase of water rights in the Middle Rio Grande Basin, *Scenario 2* represents IPR, and *Scenarios 3 and 4* represent DPR (see Fig. 1 for more detail). Two options for advanced treatment were included for each of Scenarios 2–4, both of which included microfiltration (MF) as a pretreatment step: Option A consisted of RO plus UV, and Option B consisted of O_3/BAC followed by UV, as discussed in Lee et al. [19] and Tchobanoglous et al. [6].[2] The study discussed here did not consider log removal credits for planned IPR projects in which purified wastewater is discharged to an aquifer for intended subsequent reuse because the regulatory requirements for such a system are not yet established in any state except California to the authors' knowledge. California has established regulations for IPR projects for both surface water and ground water applications [21]. In both scenarios a high degree of wastewater treatment is required including log reductions of 12, 10, and 10 for enteric virus particles, cryptosporidium oocysts, and giardia cysts, respectively. Other states regulate wastewater discharge to surface waters through NPDES permits issued under the federal Clean Water Act while ground water discharges are covered under state ground water quality regulations. In both cases, subsequent reuse of the water is not considered in federal or state regulations pertaining to the discharge.

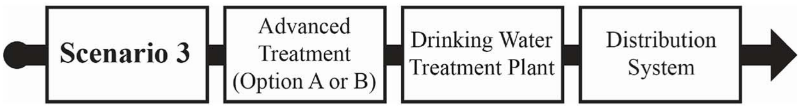
For each reuse scenario and treatment option included in this study, capital costs (including construction, engineering, and equipment) and operations and maintenance (O & M) costs (including electrical, chemical, labor, and other ongoing expenditures) were considered; cost

[1] Whatever technology is used, reliability and monitoring are critical to identifying off-spec water before it reaches the distribution system in order to protect public health; however, these topics are outside the scope of this paper.

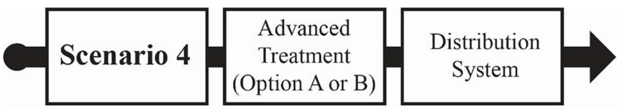
[2] Advanced treatment that included other options, such as AOPs, were also considered for inclusion in this study, but these two were ultimately selected for comparison since their performance was tested and compared by [19] and found to be nearly equivalent for the parameters tested. However, AOPs provide better removal of some compounds than UV alone. For this reason, it is important to consider its inclusion in the treatment train, as described in the previous paragraph.



a. *Scenario 2 includes conventional plus advanced wastewater treatment (2A includes RO and 2B includes O_3/BAC) followed by discharge to an environmental buffer, withdrawal, and groundwater treatment.*



b. *Scenarios 3A and 3B include conventional plus advanced wastewater treatment (3A includes RO and 3B includes O_3/BAC) followed by drinking water treatment.*



c. *Scenarios 4A and 4B are the same as 3A and 3B, respectively, except that the drinking water treatment plant is omitted prior to distribution.*

Fig. 1. Scenarios 2, 3, and 4 considered in this paper.

estimates are discussed in detail in the Methods section. With this information, the 20-year Present Worth values were estimated for each scenario and treatment option in order to compare the overall costs.

2.3. Additional infrastructure details for the scenarios

This section describes infrastructure that would be needed for each scenario in addition to the full advanced treatment facilities mentioned above (i.e., RO or O_3/BAC plus MF and UV). In Scenarios 2–4, the influent flow rate to the advanced treatment facilities was assumed to be half of the current daily average WWTP effluent flow rate at ABCWUA's Southside Wastewater Reclamation Plant, which is 25 million gallons per day (MGD).[3] The site selected for both the advanced treatment facilities and Scenario 2's environmental buffer was a large open tract of land half way between ABCWUA's existing San Juan Chama DWTP and the Southside Wastewater Reclamation Plant located twelve miles downstream from the DWTP intake structure. The distances between these three sites (i.e., the DWTP, WWTP, and the site of the environmental buffer) were used to calculate piping and pumping requirements and costs for Scenarios 2–4.

Fig. 2 shows the piping and pumping needed for each reuse scenario[4]; each stretch of piping with associated pumping is shown by *a-c* below. Some of the piping and pumping needs were similar between certain scenarios, so the piping and pumping requirements were determined between several sets of points for easy addition in later determining the piping and pumping costs for each scenario. Scenario 1 is described in subsection 2.3.1, and the details of the Scenario 2–4 piping and pumping needs, along with additional infrastructure requirements, are discussed in subsections 2.3.2 through 2.3.4.

Following the recommendations of Tchobanoglous et al. [6], an engineered storage buffer (ESB) – for this study, an aboveground covered storage basin[5] – was included for stabilization, flow retention, and quality assurance after advanced treatment (Scenarios 2–4). However, an ESB is not necessarily required for a properly designed, operated, and monitored DPR system. All scenarios with treatment option A (RO) included deep well injection into a brackish aquifer for brine disposal that was assumed to be 20 miles from the advanced treatment site. Deep well injection may not be an option in every state, and the challenges of disposing of RO concentrate from inland DPR projects have been discussed by Scruggs and Thomson [14]. Coastal communities or those with other concentrate disposal options may be able to take advantage of less expensive strategies than deep well disposal. Also, for the scenarios including RO, the Dow Water and Process Solutions Reverse Osmosis System Analysis (ROSA) software was used to estimate a daily discharge brine flow of 3.045 MGD. Input to ROSA and the output details are shown in Supplemental Materials A and B.

2.3.1. Scenario 1 (purchase of water rights)

Scenario 1 represents the purchase and transfer of additional water rights within the basin. For purposes of this paper, this scenario does not include additional infrastructure, only the capital required for the purchase.

2.3.2. Scenario 2 (IPR with advanced treatment and environmental buffer)

Scenario 2 includes injection of advanced treated water into an environmental buffer in the form of an aquifer for subsequent extraction by the utility's groundwater production wells. The injection wells were assumed to be located on the same site as the advanced treatment facilities. This scenario uses pumping and piping flow paths *a* and *b*. Path *a* consists of a 3.0 mile (4.9 km) 42 in (106.7 cm) diameter concrete pipe, which delivers WWTP effluent to advanced treatment and then to the co-located injection wells. Path *b* delivers water from the production wells to the distribution system through a 5.7 mile (9.1 km) 42 inch (106.7 cm) diameter ductile iron pipe. Pumping and piping flow path *c* is used with Scenario 2's advanced treatment option A (RO) for delivery of RO concentrate to disposal wells. Flow path *c* takes the estimated 3.045 MGD of RO concentrate to hypothetical brackish aquifer injection wells located 20 miles (32.2 km) away using a 16-inch (40.6 cm) concrete pipe.

The authors note that if the environmental buffer had been a reservoir instead of an aquifer, the water withdrawn from the buffer would be treated at the DWTP prior to distribution. In this study, it was assumed that the aquifer provided sufficient residence time (though this is not currently well defined by most US states) so that the reuse water essentially becomes ground water, requiring only groundwater treatment (i.e., chlorine addition).

2.3.3. Scenario 3 (DPR with advanced treatment and DWTP)

This scenario also uses pumping and piping flow paths *a* and *b*,

[3] During consultations with ACBWUA, staff indicated that the design flow rate for any potential future reuse facilities would likely be equal to no more than half of the daily average WWTP effluent flow, or 25 MGD.

[4] For purposes of this cost estimate, following [24], concrete piping was used to transport secondary effluent and concentrate, and ductile iron piping was used to transport advanced treated water.

[5] [30] provided guidelines for sizing ESBs. See subsection 3.1.3 for details on how storage basin costs were estimated from available size and cost data for purposes of this paper.

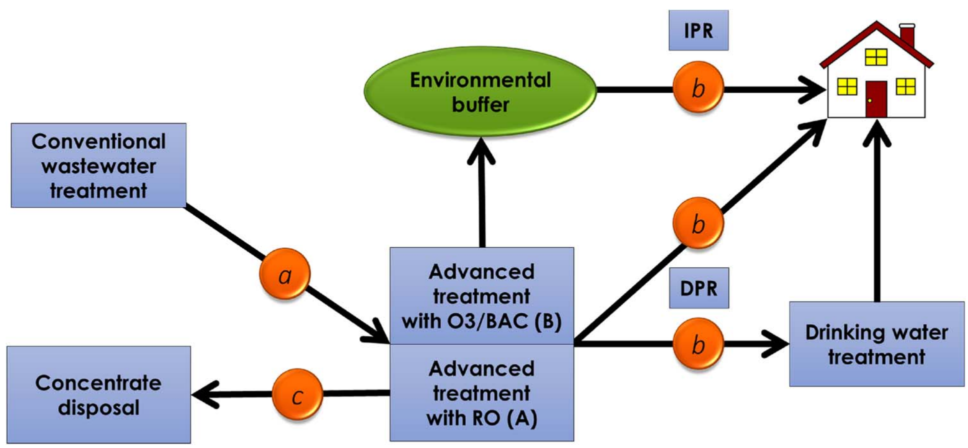


Fig. 2. Pumping and piping flow paths considered with the hypothetical reuse scenarios in this study. Flow path *a* takes the WWTP effluent to the site where both the advanced treatment and the environmental buffer will be located. In the DPR scenarios, path *b* moves the effluent from advanced treatment to the DWTP influent or the distribution system, which are practically in the same location. In the IPR scenario, path *b* moves the effluent from the environmental buffer to groundwater treatment (i.e., chlorine) and the distribution system. Path *c* takes the RO concentrate to disposal wells.

except in this case, path *a* delivers WWTP effluent to advanced treatment, and path *b* delivers water from advanced treatment to the existing DWTP prior to distribution. Also, as described for Scenario 2, pumping and piping flow path *c* is used with Scenario 3's advanced treatment option A (RO) for delivery of RO concentrate to disposal wells.

2.3.4. Scenario 4 (DPR with advanced treatment and without DWTP)

The pumping and piping flow paths used for this scenario are identical to those used in Scenario 3 above, except that advanced treated water is introduced to the utility's water distribution system instead of receiving additional treatment at the DWTP. The influent to the distribution system and the influent to the DWTP were assumed to be close enough to each other that flow path *b* could be used to estimate water transport costs in each case.

Since Scenario 4 does not include the DWTP, additional treatment at the advanced treatment plant may be required for reliability reasons and to ensure that water quality requirements are met. Additional monitoring may be required as well. However, specifying exactly what will be needed in terms of additional treatment and monitoring is challenging because DPR regulations do not yet exist [20] in any US state or at the federal level. Khan [9] suggests that, based on existing DPR installations, there is little evidence that additional treatment would be required, and that Australian DPR projects would almost certainly require additional monitoring; he provides a thorough discussion of other possible sources of additional costs for DPR.

3. Research methods

3.1. Data collection and cost conversions

Capital and O & M cost data for full advanced treatment facilities, individual treatment components, piping, pumping, and storage facilities were collected from multiple sources including costing manuals, research reports, municipal reports, and journal articles. Cost data for existing water reuse plants were also obtained through personal communication with personnel at several facilities. The following costing tools were important to the study as well:

- The WateReuse Research Foundation's (WRRF) Integrated Treatment Train Toolbox for Potable Reuse (IT^{3}PR) [22] was used to determine sizes of treatment components and estimate capital costs for each of the treatment scenarios;
- Dow Water and Process Solutions' ROSA software was used to determine the quantity of brine being discharged for scenarios that included RO;
- The Engineering News-Record (ENR) Construction Index for 2014 [43] was used to convert collected cost data from various years into 2014 dollars; and
- The RSMeans 2014 database [52] was used to convert all costs collected from other US cities into Albuquerque area values. Data points without specified locations were assumed to represent the national average and were converted from the national average to Albuquerque area values.

More detailed information regarding the data collection and cost estimates for the various scenarios and treatment options is described in the subsections that follow. As discussed by Raucher and Tchobanoglous [20], it is important to note that site-specific factors and constraints may cause capital costs to vary, and that these costs could be higher for specific projects.

3.1.1. Cost data for water rights purchase

Cost data for water rights purchases within the Middle Rio Grande basin are not publicly available because New Mexico is a non-disclosure state. Thirty-nine transactions were reported in the Middle Rio Grande valley between 2002 and 2010 [23]. Though individual water transfers are not made public, annual average prices have been reported [23]. This data was used to estimate the cost of purchase and transfer of 25 MGD [28,004 acre-feet per year (AF/yr)] of water rights.

3.1.2. Capital and O & M cost data for full advanced treatment facilities

Costs were collected for complete advanced treatment reuse facilities in California, Virginia, Washington, Texas, New Mexico, and Arizona as well as desalination facilities in Texas.[6] Costs for facilities described in the literature were included as well; this was an especially important source of data for the O_3/BAC facilities because representative capital and O & M costs were difficult to obtain. All facilities that were included in the cost data set were comparable to those included in the study's hypothetical reuse scenarios. Complete facility O & M costs included power, chemicals, offsite residuals disposal, materials maintenance and repairs, supervisory control and data acquisition (SCADA) systems and instrumentation, laboratory and monitoring work, labor, and miscellaneous service contracts, consultant fees, and office supplies. (Costs related to primary and secondary treatment at the WWTP were not included.) Complete facility capital costs included

[6] Initially, cost data for the complete advanced treatment plants *and* individual components were collected and compiled. However, it became apparent that the individual component data exhibited wide variability for capital and O & M costs, likely because of variability in what was included as part of each component's costs (e.g., chemical addition to the influent for the component, energy costs for associated equipment, inclusion of unit processes that were in series with the component, etc.). Since the complete plant data exhibited far less variability, as will be shown in Fig. 3, it was used as the primary source of data for the study calculations.

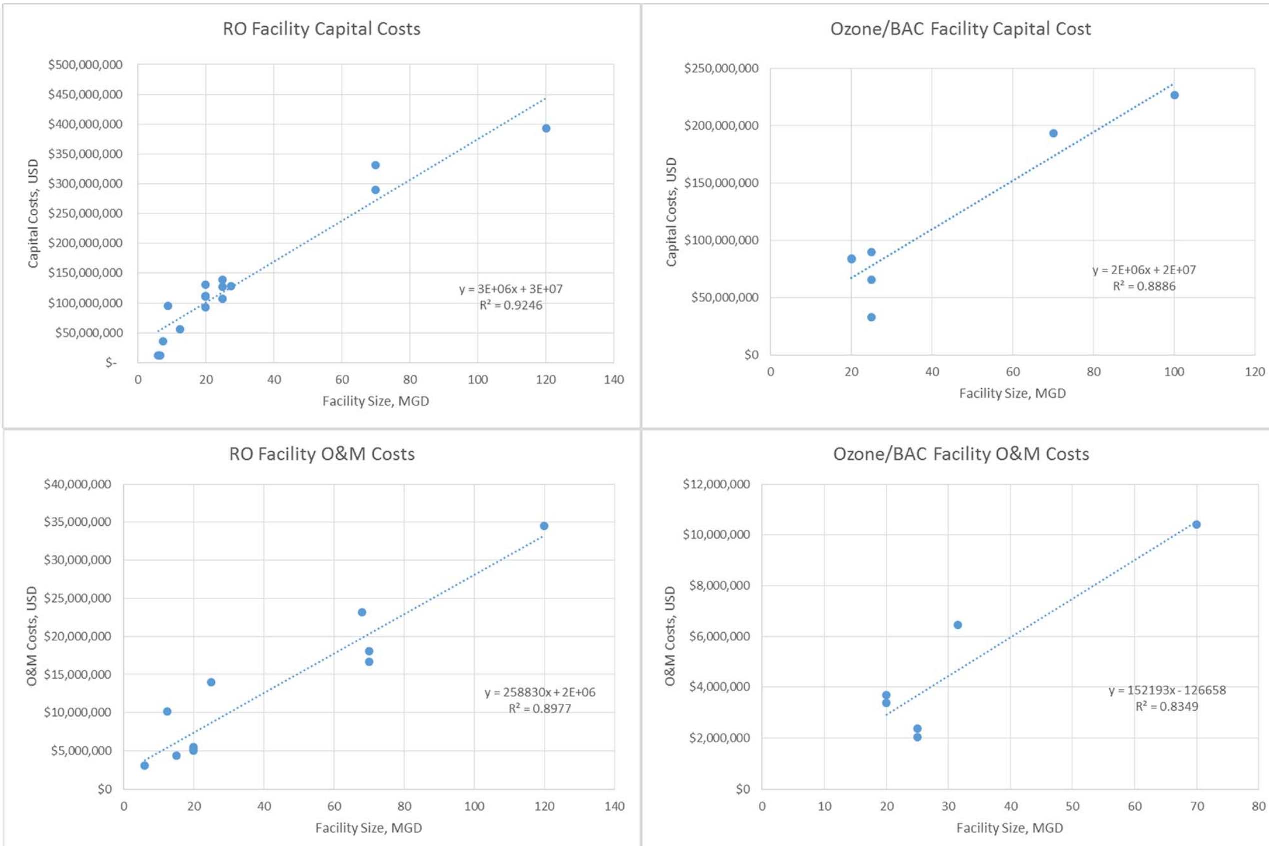


Fig. 3. Relationship between Plant Capacity and Capital and O & M Costs for Full-scale RO and O_3/BAC Facilities.

microfiltration, ozone, BAC, and UV for the O^3/BAC option, and microfiltration, RO, and UV for the RO option.[7] Facilities with a capacity of less than 5 MGD were removed from the data set since they lacked economies of scale that a 25 MGD plant would likely exhibit. Each cost was converted to 2014 dollars using the ENR index and then converted to Albuquerque area values using the 2014 RSMeans index of construction cost multipliers. The resulting capital and O & M cost data for complete advanced treatment facilities are shown in Supplemental Material C and Supplemental Material D, respectively.

The relationship between plant capacity and capital and O & M costs was determined by regression analysis of cost data from the full-scale plants, which ranged in capacity from 6 to 120 MGD (see Supplemental Materials C and D). Linear regression analysis of the data resulted in reasonably good fits with R^2 values ranging from 0.83 to 0.92, as shown in Fig. 3. These relationships were used to estimate capital and O & M costs for a 25 MGD plant.

3.1.3. Capital and O & M cost data for additional infrastructure

The costs of additional required infrastructure (i.e., piping; pumping; IPR wells and pumps; treated water storage basins; brine disposal wells; and replacement equipment for ozone, UV, and membranes) were included for each scenario. The infrastructure capital and O & M cost data were adjusted to 2014 Albuquerque dollars. A complete list of the equations and data used to determine capital costs can be found in Supplemental Material E. For most infrastructure items, there were several data points or multiple means of estimating their costs. In these cases, capital costs were estimated by averaging the multiple cost data points.

O & M costs for piping and pumping in each of flow paths *a-c* were determined using a per mile per year cost provided by Woods et al. [24]. Similar to the capital costs, O & M costs for other infrastructure were estimated by averaging data from multiple sources. O & M costs for treatment through the DWTP were included for Scenarios 1 and 3. A summary of the O & M cost calculation methods can be found in Supplemental Material F.

3.1.4. Capital cost data for replacement treatment components

The components comprising the reuse scenarios had different useful service life estimates. The useful service life estimates of the categories of equipment included in the reuse scenarios are shown in Supplemental Material G. The equipment related to RO, O_3/BAC, and IPR wells and pumps is broken out separately in order to show the details of replacement requirements within each system.

Any equipment with a service life of less than 20 years needed to be replaced as appropriate during the 20-year project life. As shown in Supplemental Material G, the equipment requiring replacement during the 20-year project life is related to UV, ozone, RO, and pumps. The present worth of all equipment requiring replacement in each scenario is shown in Supplemental Material H. The capital costs for replacing UV and ozone equipment were estimated by contacting equipment manufacturers and requesting equipment-only costs for both technologies using the treatment parameters provided by the IT^3PR tool. The capital costs of membranes came from WaterAnywhere.com [58] and those for pumping were the same as the costs originally used in the various flow paths.

3.2. Present worth calculations

The 20-year present worth, also known as the net present value [25,26], for each flow and treatment scenario was calculated using the following equations [24]:

[7] In a few instances, specific details were not provided about what comprised the total cost provided for O & M or capital.

$$V_{salv} = \frac{C_{cap}(t_{life} - (t_{total} - t_{build}))}{t_{life}} \cdot \frac{1}{(1+i)^{(t_{total} - t_{build})}}$$

$$C_{pres} = C_{cap}\frac{1}{(1+i)^{t_{build}}} + C_{OM}\frac{(1+i)^{(t_{total} - t_{build})} - 1}{i(1+i)^{t_{total}}} - V_{salv}(1+i)^{-t_{build}}$$

where: C_{pres} = the 2014 present worth cost in USD;
C_{cap} = capital costs in USD;
C_{OM} = annual operations and maintenance costs in USD;
V_{salv} = salvage value in USD;
t_{build} = project initiation time, 0 years (i.e., immediate initiation);
t_{total} = project lifetime, assumed to be 20 years;
t_{life} = variable number of years depending on equipment life expectancy;
i = discount rate, a range of 3–8% was examined as discussed in Section 4.

In cases where a piece of equipment's useful life was less than 20 years, the present worth of the replacement equipment was determined using the present worth equation and adding the result to the total present worth cost. In these cases, t_{build} was the year the equipment needed to be replaced. A range of discount rates was examined as recommended by the US Office of Management and Budget [27] and the US Department of Agriculture's guidance specific to non-watershed based water projects [28].

3.3. Limitations and assumptions

In estimating the costs for the various reuse scenarios, a number of assumptions were made and some costs were excluded. First and foremost, differences among the scenarios in produced water quality were not evaluated; treatment scenarios appropriate for the inland context and their associated costs as reported in the literature formed the basis of the cost estimates included herein. Protection of public health is, of course, a priority. Communities evaluating IPR or DPR will need to consider applicable state guidance and regulations pertaining to pathogen removal, treatment component redundancy, acceptable salinity levels, monitoring requirements, operator qualifications and staffing, and other factors. If salinity is an issue, as is often the case in the arid southwest, it is important to note that only RO can control salinity, which may affect process selection.

Land acquisition costs for siting new reuse and related facilities were not considered in this analysis; it was assumed that ABCWUA would already have any needed land. It was also assumed that wastewater effluent would be available in the quantities specified herein and that the effluent could be diverted from the WWTP without any added cost or impact to the ABCWUA. Potential water rights constraints and the value of water lost to RO concentrate disposal were not considered (except for the hypothetical purchase of water rights described in Scenario 1). Regulatory and permitting costs, such as for plant construction or permitting or for injection well permits were not considered, and the advanced treatment requirements for IPR and DPR were assumed to be the same due to the current lack of regulatory distinction between these scenarios. Multiple assumptions were made regarding the piping and conveyance of the wastewater effluent, treated reuse water, and brine stream: distances were calculated using straight lines from site to site and elevation changes between sites were not considered when calculating pumping requirements.

Further, the ABCWUA's existing production wells were assumed to be adequate for the IPR scenarios rather than requiring new wells and associated infrastructure to deliver water to the distribution system. If new wells are needed, it will add capital and operating costs to the estimates presented here. Similarly, Scenario 3 relies on existing treatment capacity at the DWTP. This is justified because it is based on replacing surface water with recycled water; there would be no net increase in demand. Due to site-specific factors and other considerations and constraints, actual costs may vary.

Other limitations to the cost estimates included limited availability of O & M data for O_3/BAC systems and lack of detailed information regarding what elements were included in capital and O & M costs for systems described in the literature and other sources. The IT^3PR operation manual also specified the following limitations for cost estimates produced by the tool: "ancillary and site-specific costs, in particular, the cost of RO or NF concentrate disposal, is not included in the estimates" [29].

Finally, monitoring and process control costs were not explicitly included in this study. Testing and analysis methods and other quality assurance/quality control strategies for potable reuse are currently an active area of research; while these costs tend to be high now, they may decrease over time. In this study, these costs were included in O & M cost estimates for many of the complete advanced treatment facilities, though a few reports did not specify whether or not they were included. Monitoring requirements will likely be more extensive for DPR than IPR. For example, DPR may require more continuous on-line monitoring of treatment processes than IPR [20].

4. Results and discussion

The 20-year present worth values for the scenarios examined in this paper are shown in Table 1 below, along with the initial capital, recurring capital for replacement equipment, and O & M costs. The recurring capital costs are shown as 20-year present worth values. The initial capital, recurring capital, and O & M costs are broken out separately in order to show which scenarios are more expensive up front and which have higher costs throughout the project life. Discount rates ranging from 3 to 8 percent were examined; Table 1 displays the results for the 3% rate and Fig. 4 displays this information graphically. A sensitivity analysis was performed for the 3–8 percent range of discount rates and is presented in Supplemental Material I; the total present worth values shown for Scenarios 2–4 in Table 1 follow the same pattern for all discount rates examined.

All four categories of costs shown above are important in understanding the economic impact of each scenario. For example, looking at O & M or replacement costs in isolation could give a false impression of the economic feasibility of a scenario for a given community.

Scenario 1, the purchase of water rights, was the most costly of the scenarios considered. The only costs included in this scenario were the initial capital associated with the acquisition of 28,004 acre-feet/year

Table 1
Costs of Water Supply Scenarios, i = 3%.

Cost Type	Water Supply Scenarios and Advanced Treatment Options						
	1 – Purchased water	*2 – IPR*		*3 – DPR*		*4 – DPR*	
		RO	O_3/BAC	*RO*	O_3/BAC	*RO*	O_3/BAC
Initial Capital Costs, USDx10^6	494.1	243.6	181.6	178.3	116.3	178.3	116.3
20-year Present Worth of Replacement Equipment Costs, USDx10^6	0	20.6	60.9	17.1	57.4	17.1	57.4
O & M Costs, USDx10^6/year	3.7	9.4	4.4	12.9	8.0	9.2	4.3
20-year Total Present Worth, USDx10^6	548.8	378.9	285.9	368.8	275.8	314.1	221.0

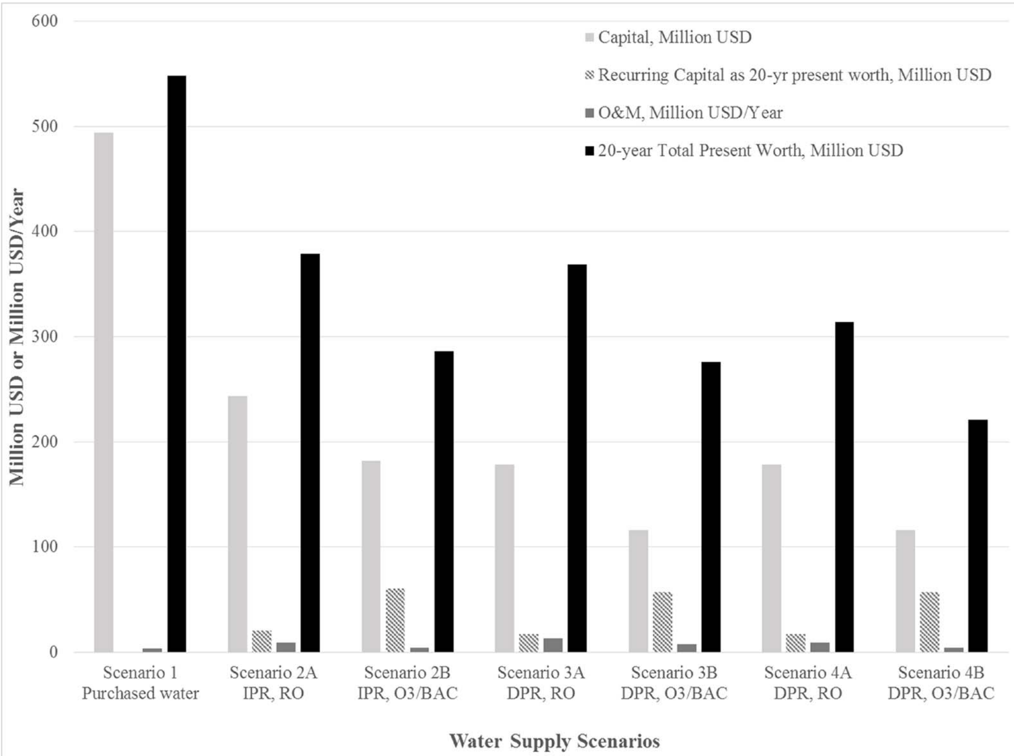


Fig. 4. Costs of Water Supply Scenarios, $i = 3\%$.

of water rights and the O & M associated with treating that water at the DWTP. Possible impediments to this scenario include the availability of the water rights and institutional constraints surrounding rights transfers. Purchasing rights in this quantity could prove problematic considering that transfers within the basin between 2000 and 2009 totaled only 3758 acre-feet. Regarding institutional constraints, the administrative process timeframe for water rights transfers can be up to 2 years [23].

For Scenarios 2–4, as expected, the O_3/BAC options had significantly lower total present worth costs relative to the RO options since initial capital and O & M costs for O_3/BAC plants are generally less than for RO plants, in part due to RO's concentrate disposal requirement and high energy consumption. Findings presented here follow the expected pattern for initial capital and O & M costs. However, the equipment replacement costs for the O_3/BAC options were higher than for the RO options in all scenarios for two reasons.[8] The first is that a higher intensity and more costly UV system is needed for the O_3/BAC options due to the quality difference in feed water influent to the equipment. The second reason is the cost associated with replacing the O_3 equipment, which is not included in the RO options. It should also be noted that while membrane replacement costs for the RO options are included, they are relatively small.

Certain limitations in the data available for estimating the recurring equipment replacement costs should be noted. First, a limited amount of data was available for estimating the ozone and UV equipment replacement costs associated with the O_3/BAC options. Of the seven data points available, only one was from an actual operational plant, making the cost estimates almost entirely theoretical. Also, there were large ranges in capacity (and intensity for UV) across the data set for ozone and UV equipment installations; rather than taking averages of this data to estimate ozone and UV equipment replacement costs, manufacturers were contacted, provided with system specifications, and asked for an estimate of equipment replacement costs for inclusion in the present worth calculations. Costs were collected from Pinnacle Ozone Solutions LLC for ozone equipment and Calgon Corp. for UV equipment.

In addition, the disposal of concentrate in the RO options was handled fairly simplistically. A radius of 20 miles was assumed to be the outer limit in which the ABCWUA would likely find a suitable deep brackish or saline aquifer for concentrate disposal. If a suitable aquifer is not available within a reasonable radius, an alternate means of disposal, such as evaporation ponds or brine concentration, could be considered, though the costs may be higher [20].

Scenario 2, IPR with advanced treatment, had higher overall costs as compared to Scenarios 3 and 4 for DPR due to inclusion of an environmental buffer. It should be noted that Scenario 2's cost estimates are likely on the low end because the advanced treatment and aquifer injection facilities were assumed to be co-located, eliminating the need for conveyance costs between advanced treatment and aquifer injection; also, as previously mentioned, ABCWUA's existing system of production wells was utilized rather than adding costs for a new well field. In addition, degradation of water quality through IPR could occur if the aquifer is not of high quality, which may increase capital and O & M costs if additional equipment and treatment is needed to bring the water up to standards. Scenario 2 was included because past research has found higher public support for IPR than DPR (e.g., [31]).

Scenarios 3 and 4 – DPR with advanced treatment − were found to have the lowest present worth costs.[9] Scenario 4 had the lowest cost since finished water goes to the distribution system rather than to the DWTP as it does in Scenario 3; this cost would be even lower if the scenario had been given "credit" for obviating the need for DWTP plant capacity. While lowest in cost, it is possible that these two scenarios could face the greatest amount of resistance from community members and/or regulators [32,33]. A community survey would be needed to understand attitudes toward and acceptance of DPR in a given local context, community outreach and education programs would be

[8] Note that UV lamp replacement is included in the O & M costs rather than the equipment replacement costs.

[9] Again, we note that the IPR options were not given "credit" for any additional treatment through the environmental buffer since New Mexico regulations do not yet specify what the treatment differences, if any, should be for IPR versus DPR.

required to aid the public in understanding the details of its water supply options, and regulators would need to accept the treatment schemes. It is not likely that Scenario 4 (as described here) would be acceptable to regulators and the public in the near-term until more experience with DPR has been gained and monitoring and process control equipment and technologies become further advanced [20].

5. Conclusions and future research

Most planned potable water reuse research to date has focused on large coastal communities. Significant knowledge gaps exist regarding potable reuse in the arid, inland context, making it difficult for inland water managers to understand the feasibility of potable reuse for their communities. This research aims to inform decision-making about planned potable reuse in small-to-medium-sized, arid inland communities by estimating the present worth of several water supply scenarios, including IPR and DPR that are appropriate for the inland context. The results showed that the present worth of IPR was higher than for DPR and that the type of advanced treatment included in an IPR or DPR scenario had a significant impact on the scenario's overall present worth (i.e., options including RO were more expensive than those including O_3/BAC). Of course, cost is not the only consideration: any of these scenarios must be acceptable to regulators and the public and approvable from a water rights perspective. Purchase of water rights as an alternative means of increasing the local water supply is likely more expensive and may involve institutional challenges and availability issues.

More work is needed to better understand the feasibility of potable reuse in arid, inland communities. Recommendations for future research include studies related to public acceptance and perceptions of potable reuse and willingness to pay for implementation of various reuse options. The present worth estimates in this paper can serve as the starting point for community focus group and/or survey research to understand water customers' willingness to pay for rate increases to maintain their current level of service in drought periods. Also needed are large surveys in arid, inland communities to better understand public perception of different water reuse technologies and scenarios, how different educational materials affect public perception of water scarcity and attitudes toward potable reuse, and how demographics and local context affect these sentiments. Another critical area for further research is on concentrate management options, which will be essential for inland communities to understand the feasibility of potable reuse. This study has attempted to fill some existing knowledge gaps in order to help water utilities and managers in small-to-medium sized arid inland communities make more informed decisions for long-range sustainable water planning.

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Supplemental Materials.

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