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Indirect potable reuse treatment processes as shown at the Fred Hervey Water Reclamation Plant in El Paso, Texas.

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THE COST 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 is substantially higher than for direct potable reuse because of additional pumping and piping requirements, and scenarios including reverse osmosis for advanced treatment have significantly higher present worth values than those including ozone/biological activated carbon. Costs aside, any scenario must also be acceptable to regulators and the public and approvable from a water rights perspective.

Keywords: Water scarcity, indirect potable reuse, direct potable reuse, treatment costs, present worth, resource management, sustainable community planning

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1.0 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 (Grant et al., 2012; Hering et al., 2013; Hurlimann et al., 2009). Indirect and direct potable water 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 (Grant et al., 2012). With planned IPR, highly treated wastewater treatment plant (WWTP) effluent is held for a specified amount of time in an environmental buffer, such as a reservoir or aquifer, prior to being directed to a drinking water treatment plant (DWTP) (United States Environmental Protection Agency, 2012). 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 (United States Environmental Protection Agency, 2012; Law, 2008; Tchobanoglous et al., 2011; Leverenz et al., 2011).

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 (Rodriguez et al., 2009), 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 (Leverenz et al., 2011; Khan, 2013). IPR has been shown to be more expensive than DPR (Law, 2008; Tchobanoglous et al. 2011; Leverenz et al., 2011; Khan, 2013; Venkatesan et al., 2011) and have a greater carbon footprint (Gutzler, 2012; Law, 2008; Khan, 2013) because of the additional piping, pumping, and treatment; however, IPR’s costs are context specific since they depend on the characteristics and location of the environmental buffer. Far fewer DPR systems exist worldwide; while a facility in Windhoek, Namibia has been operating successfully in various configurations since 1968 (Crook, 2010), 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 scattered throughout the inland Southwestern US (United States Bureau of Reclamation, 2005), most of the research on potable reuse has focused on large coastal communities with relatively high mean household incomes (United States Census Bureau, 2012), such as Orange County, Los Angeles, and San Diego, CA. 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 (Leverenz et al., 2011). 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.

2.0 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 suitable 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 must be studied for a broader understanding of water management alternatives (National Research Council, 2012), 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 (United States Bureau of Reclamation, 2005). 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 (United States Bureau of Reclamation, 2005); (2) the population is highly diverse with a relatively low mean household income (United States Census Bureau, 2012); 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 biggest water utility in NM and provides water supply and wastewater collection and treatment for over 500,000 people (Thacher, 2014). 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 managers and decision makers in arid inland communities can use the study results to help them consider the costs and constraints of various potable reuse options.

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 (Lee et al., 2009), and (3) recovery of only a fraction of the feed water, an important limitation in communities facing serious water shortages. Coastal communities can dispose of concentrate into the sea (Leverenz et al., 2011), but inland communities must find alternative disposal options. It is reasonable for inland communities to consider advanced treatment options that do not include RO (Tchobanoglous et al., 2011) in order to avoid the technologies' drawbacks (Leverenz et al., 2011), 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. A promising alternative to RO is ozone plus biofiltration or biological activated carbon (O_3/BAC), which provides treatment comparable to RO, including removal of contaminants of emerging concern (CECs), while using less energy and without creation of a brine stream (Lee et al., 2012).[1] The O_3/BAC option is less expensive than the RO option because of 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 or grey literature.

Several scenarios to increase the potable water supply were considered in this study; these scenarios complement those considered by Raucher and Tchobanoglous (2014). The scenarios considered were inland IPR and DPR, as discussed by Tchobanoglous and others (2011), 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 Figure 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 ultraviolet (UV) disinfection, and Option B consisted of O_3/BAC followed by UV, as discussed in Lee et al. (2012) and Tchobanoglous et al. (2011).[2] For purposes of this study, treatment "credit" for time in the environment was not given to the IPR options because regulations have not yet defined the difference between the level of advanced treatment required

[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] Other advanced treatment options, including advanced oxidation processes, were considered for inclusion as well, but these two were ultimately selected for comparison since their performance was tested and compared by Lee and others (2012) and found to be nearly equivalent.

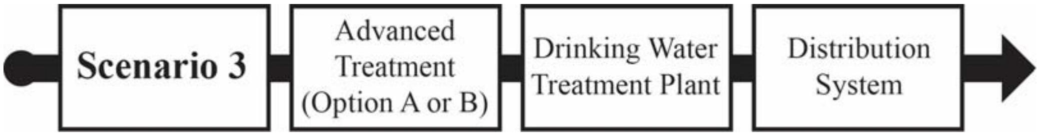
for IPR versus DPR; it is possible that the amount of treatment for the IPR options will be less than that required for DPR, but that distinction is not made here. For each reuse scenario and treatment option, capital costs (including construction, engineering, and equipment) and operations and maintenance (O&M) costs (including electrical, chemical, labor, and other ongoing expenditures) were considered; cost 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

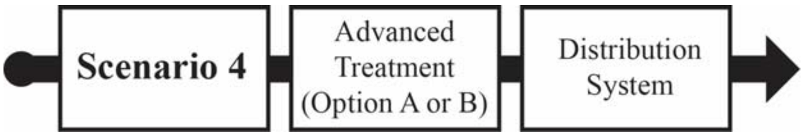
This section describes infrastructure that would be needed for each scenario in addition to the full advanced treatment facilities mentioned above (i.e., RO or O_3/BAC plus MF and UV). In Scenarios 2-4, the influent flow rate to the advanced treatment facilities was assumed to be half of the current 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 downstream Southside Wastewater Reclamation Plant. The distances between these three sites (i.e., the DWTP, WWTP, and the selected site) were used to calculate piping and pumping requirements and costs for Scenarios 2-4.

***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 drinking water treatment.**

[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.



b. **Scenarios 3A and 3B are the same as 2A and 2B, respectively, except that the environmental buffer is omitted.**



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.

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

Figure 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. (2011), 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). All scenarios with treatment option A (RO) included deep well injection into a brackish aquifer for brine disposal; a specific, appropriate brackish aquifer was not selected, but for purposes of this study the hypothetical deep well injection site was 20 miles from the advanced treatment site. 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 Appendices A and B.

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[4] For purposes of this cost estimate, following Woods and others (2013), concrete piping was used to transport secondary effluent and concentrate, and ductile iron piping was used to transport advanced treated water.
[5] Salveson and others (2016) 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.

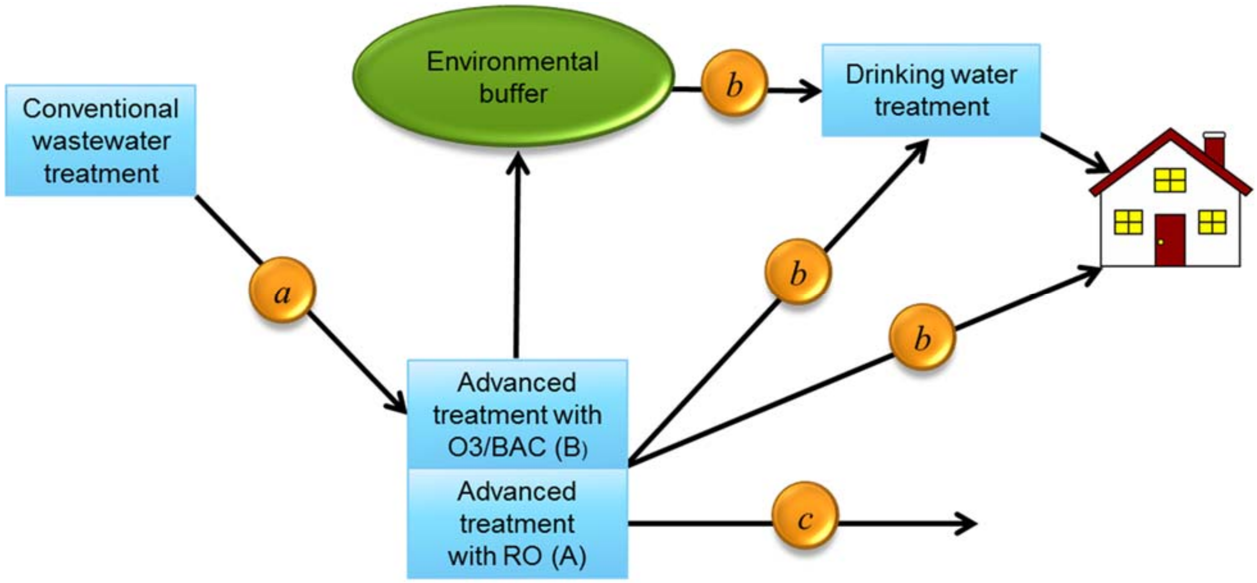

Figure 2. Pumping and piping flow paths considered with the hypothetical reuse scenarios in this paper. Flow path a takes the WWTP effluent to the site where both the advanced treatment and the environmental buffer will be located; path b moves the effluent from advanced treatment or the environmental buffer to the DWTP influent or the distribution system, which are practically in the same location; and path *c* takes the RO concentrate to disposal wells.

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, Environmental Buffer, and DWTP).

Scenario 2 includes injection of advanced treated water into an environmental buffer in the form of a groundwater aquifer for extraction at a later time through ABCWUA's groundwater production wells, which are located across the service area. 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 inch (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 existing DWTP through a 5.7 mile (9.1 km) 42 inch (106.7 cm) diameter ductile iron pipe. Pumping and piping flow path *c* is also used with Scenario 2's advanced treatment option A (RO) for delivery of RO brine to disposal wells. Flow path *c* takes the estimated 3.045 MGD of RO brine to a hypothetical brackish aquifer injection point 20 miles (32.2 km) away using a 16-inch (40.6 cm) concrete pipe.

2.3.3 Scenario 3 (DPR with Advanced Treatment and DWTP).
The pumping and piping flow paths used for this scenario are identical to those used in Scenario 2 above, except that water is not directed to injection wells since Scenario 3 does not include an environmental buffer.

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 flow path *b* goes to the drinking water distribution system instead of the influent to 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.

3.0 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^3PR) (Trussell et al., 2015a) 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 was used to convert collected cost data from various years into 2014 dollars; and
- The RSMeans 2014 database 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.

3.1.1. Cost Data for Water Rights Purchase.

Cost data for water rights purchases within the Middle Rio Grande basin are scarce; 39 transactions were reported as occurring upstream of Isleta Dam between 2002 and 2010 (Payne and Smith, 2011). Individual water transfers of this type are not generally made public, though annual average prices have been reported (Payne and Smith, 2011). This limited data was used to estimate the cost of purchase and transfer of 25 MGD, or 28,004 acre feet per year, 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

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[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 Figure 3, it was used as the primary source of data for the study calculations.

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 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 Appendix C and Appendix 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 Appendices 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 Figure 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; ASR 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 Appendix 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. (2013). Similar to the capital costs, O&M costs for other infrastructure was estimated by averaging data from multiple sources. O&M costs for treatment

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

through the DWTP were included for all scenarios except Scenario 4. A summary of the O&M cost calculation methods can be found in Appendix 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 Appendix G. The equipment related to RO, O_3/BAC, and ASR 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 Appendix 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 Appendix 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^{3}PR tool. The capital costs of membranes came from WaterAnywhere.com 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 (Blank and Tarquin, 2008; Carmichael et al., 2011), for each flow and treatment scenario was calculated by inputting the capital and O&M costs into the following equations (Woods et al., 2013):

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

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

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, 20 years;
t_{life} = variable number of years depending on equipment life expectancy;
i = discount rate, range of 3 to 8% 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 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 (United States Office of Management and Budget, 1992) and the US Department of Agriculture's guidance specific to non-watershed based water projects (United States Department of Agriculture, 2014).

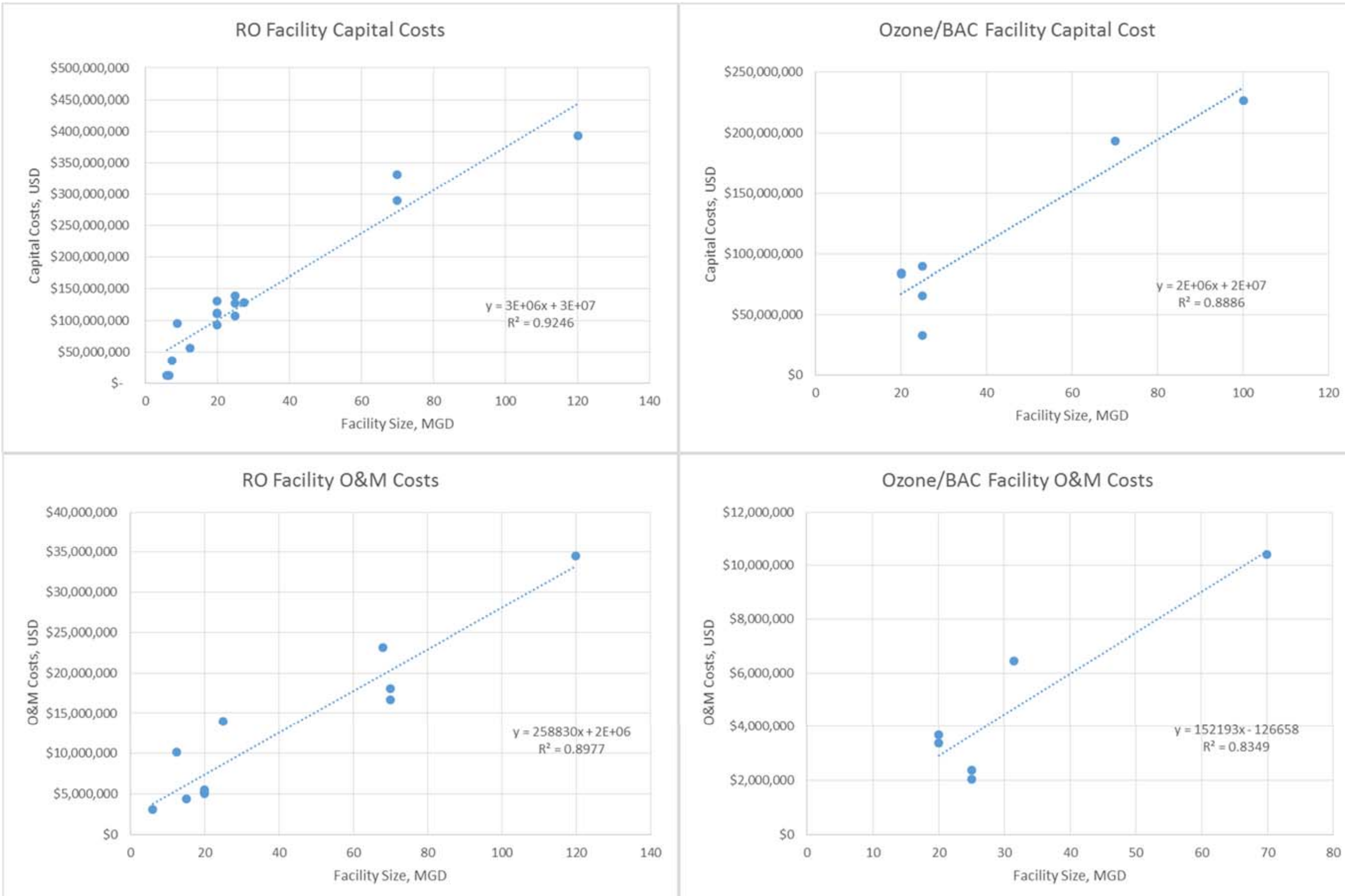

Figure 3. Relationship between Plant Capacity and Capital and O&M Costs for Full-scale RO and O3/BAC Facilities.

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. Communities interested in IPR or DPR will need to consult with their state environment departments regarding applicable guidance or regulations on acceptable salinity levels, pathogen removal, treatment component redundancy requirements, and other design-related factors.

Land acquisition costs for siting new reuse and related facilities were not considered in the present worth calculations; 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. Any potential water rights implications 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 injection well permits or for operating a potable reuse facility, were not taken into account either, and the advanced treatment requirements for IPR and DPR were assumed to be the same due to the current lack of regulatory distinction in this area. 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 system of groundwater production wells was incorporated into the IPR scenarios rather than including the costs of a new well system, and the new infrastructure that would be required to introduce water to the DWTP and the distribution system was not considered; these limitations will lead to underestimation of the costs associated with various scenarios. Similarly, Scenarios 2 and 3 rely on existing treatment capacity at the DWTP (rather than including capital costs for additional DWTP capacity), while Scenario 4 does not, thus disadvantaging Scenario 4 in the cost comparison.

Other limitations to the cost estimates included limited availability of O&M data for O_3/BAC systems, and occasional lack of specificity about exactly what elements were included in capital and O&M costs for systems described in the literature and other sources. The IT^{3}PR 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" (Trussell et al., 2015b). In addition, 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 data obtained for many of the complete advanced treatment facilities, though a few data sets did not specify whether or not they were included.

4.0 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 Figure 4 displays this information graphically. A sensitivity analysis was performed for the 3 to 8 percent range of discount rates and is presented in Appendix I; the total present worth values shown for Scenarios 2-4 in Table 1 follow the same pattern for all discount rates examined.

Cost Type	**Water Supply Scenarios and Advanced Treatment Options**						
	1	*2*		*3*		*4*	
		A	*B*	*A*	*B*	*A*	*B*
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	20.5	60.9	17.1	57.4	17.1	57.4
O&M Costs, USDx10^6/year	3.7	13.0	8.1	12.9	8.0	9.2	4.3
20-year Total Present Worth, USDx10^6	**548.8**	**433.6**	**340.6**	**368.8**	**275.8**	**314.1**	**221.0**

Table 1. Costs of Reuse Scenarios, i=3%.

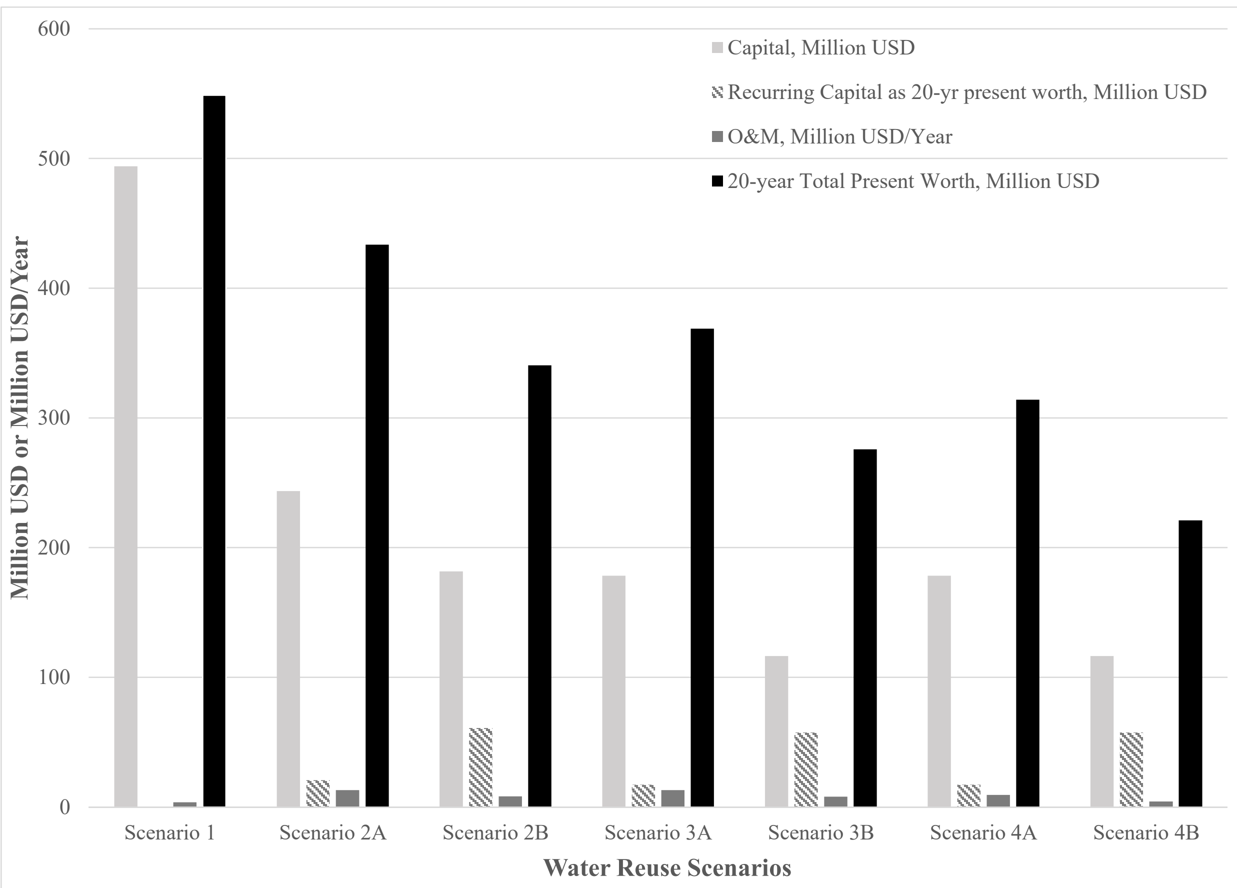

Figure 4. Cost of Reuse Scenarios, i=3%.

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 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 3,758 acre-feet. Regarding institutional constraints, the administrative process timeframe for water rights transfers can be up to 2 years (Payne and Smith, 2011).

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 brine 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

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

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 brine 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 brine disposal. If a suitable aquifer is not available within a reasonable radius, an alternate means of brine disposal, such as evaporation ponds or brine concentration, could be considered, though the costs may be higher (Raucher and Tchobanoglous, 2014).

Scenario 2, IPR with advanced treatment, had higher costs in all categories 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 (in addition to what already exists at the DWTP) 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., Millan et al., 2015).

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; a community survey would need to be performed to understand

[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.

attitudes toward and acceptance of DPR for a given local context, and regulators would need to accept the treatment schemes. It is not likely that Scenario 4 (as described here) would actually be implemented for reasons of aesthetics (i.e., the water sent to the distribution system would likely be warmer than water coming out of the DWTP).

5.0 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 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. This study has attempted to fill some of these 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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APPENDICES

APPENDIX A: ROSA Detailed System and Flow Report for RO (A Scenarios).

Reverse Osmosis System Analysis for FILMTEC™ Membranes — ROSA 9.1 ConfigDB u399339_282
Project: A SCENARIOS RO SYSTEM — Case: 1
Jason Herman, UNM — 8/23/2015

Project Information:

Case-specific:

System Details

Feed Flow to Stage 1	17361.00 gpm	Pass 1 Permeate Flow	15246.17 gpm	Osmotic Pressure:	
Raw Water Flow to System	17361.00 gpm	Pass 1 Recovery	87.82 %	Feed	6.54 psig
Feed Pressure	100.00 psig	Feed Temperature	77.0 F	Concentrate	51.10 psig
Flow Factor	0.85	Feed TDS	548.00 mg/l	Average	28.82 psig
Chem. Dose	None	Number of Elements	4248	Average NDP	71.63 psig
Total Active Area	1869120.00 ft²	Average Pass 1 Flux	11.75 gfd	Power	1022.36 kW
Water Classification: Wastewater with Generic membrane filtration, SDI < 3				Specific Energy	1.12 kWh/kgal

Stage	Element	#PV	#Ele	Feed Flow (gpm)	Feed Press (psig)	Recirc Flow (gpm)	Conc Flow (gpm)	Conc Press (psig)	Perm Flow (gpm)	Avg Flux (gfd)	Perm Press (psig)	Boost Press (psig)	Perm TDS (mg/l)
1	ECO-440i	422	6	17361.00	95.00	0.00	8557.24	86.52	8803.76	11.38	30.00	100.00	3.78
2	ECO-440i	196	6	8557.24	81.52	0.00	4108.61	72.56	4448.63	12.38	0.00	0.00	10.32
3	ECO-440i	90	6	4108.61	102.56	0.00	2114.83	92.93	1993.78	12.08	0.00	35.00	30.32

Pass Streams (mg/l as Ion)									
Name	Feed	Adjusted Feed	Concentrate			Permeate			
			Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Total
NH4+ + NH3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	215.57	215.57	435.82	903.31	1743.68	1.49	4.06	11.93	3.60
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HCO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl	332.43	332.43	672.08	1393.00	2688.93	2.29	6.26	18.39	5.56
F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SO4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SiO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TDS	548.00	548.00	1107.90	2296.32	4432.61	3.78	10.32	30.32	9.16
pH	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Design Warnings

-None-

Solubility Warnings

-None-

Stage Details

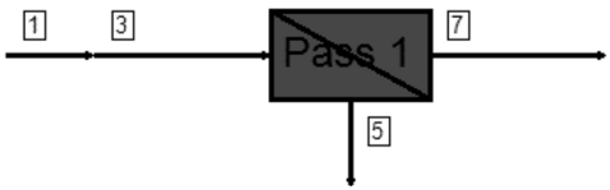
Stage 1	Element	Recovery	Perm Flow (gpm)	Perm TDS (mg/l)	Feed Flow (gpm)	Feed TDS (mg/l)	Feed Press (psig)
	1	0.10	3.92	2.16	41.14	548.00	95.00
	2	0.10	3.74	2.61	37.22	605.50	93.06
	3	0.11	3.57	3.20	33.48	672.90	91.36
	4	0.11	3.39	3.97	29.91	752.79	89.86
	5	0.12	3.21	5.02	26.52	848.59	88.57
	6	0.13	3.02	6.49	23.30	964.96	87.46
Stage 2	Element	Recovery	Perm Flow (gpm)	Perm TDS (mg/l)	Feed Flow (gpm)	Feed TDS (mg/l)	Feed Press (psig)
	1	0.10	4.44	5.42	43.66	1107.90	81.52
	2	0.11	4.19	6.76	39.22	1232.61	79.44
	3	0.11	3.93	8.54	35.04	1379.10	77.63
	4	0.12	3.67	10.98	31.10	1552.41	76.06
	5	0.12	3.39	14.38	27.43	1758.52	74.70
	6	0.13	3.08	19.23	24.05	2004.24	73.54
Stage 3	Element	Recovery	Perm Flow (gpm)	Perm TDS (mg/l)	Feed Flow (gpm)	Feed TDS (mg/l)	Feed Press (psig)
	1	0.10	4.64	15.74	45.65	2296.32	102.56
	2	0.10	4.28	19.98	41.01	2554.25	100.37
	3	0.11	3.90	25.68	36.73	2849.39	98.45
	4	0.11	3.51	33.41	32.83	3184.98	96.77
	5	0.11	3.11	44.00	29.32	3562.63	95.31
	6	0.10	2.71	58.63	26.21	3980.65	94.04

APPENDIX B: ROSA System Design Overview Report for RO (A Scenarios).

Project: A SCENARIOS RO SYSTEM
Prepared By: Jason Herman
UNM

ROSA 9.1 ConfigDB u399339_282
Case: 1
8/23/2015

System Design Overview



Raw Water TDS	548.00 mg/l	% System Recovery (7/1)	87.82 %
Water Classification	Wastewater with Generic membrane filtration, SDI < 3	Flow Factor (Pass 1)	0.85
Feed Temperature	77.0 F		

Pass #	**Pass 1**		
Stage #	**1**	**2**	**3**
Element Type	ECO-440i	ECO-440i	ECO-440i
Pressure Vessels per Stage	422	196	90
Elements per Pressure Vessel	6	6	6
Total Number of Elements	2532	1176	540
Pass Average Flux	11.75 gfd		
Stage Average Flux	11.38 gfd	12.38 gfd	12.08 gfd
Permeate Back Pressure	30.00 psig	0.00 psig	0.00 psig
Booster Pressure	100.00 psig	0.00 psig	35.00 psig
Chemical Dose	-		
Energy Consumption	1.12 kWh/kgal		

Pass 1			
Stream #	**Flow (gpm)**	**Pressure (psig)**	**TDS (mg/l)**
1	17361.00	0.00	548.00
3	17361.00	100.00	548.00
5	2114.83	92.93	4432.61
7	15246.17	-	9.16
7/1	**% Recovery**	87.82	

Project Information:

Design Warnings:
-None-

Solubility Warnings:
-None-

APPENDIX C: Capital Costs for Full Advanced Treatment Facilities and Water Rights Purchase.

Facility Name	Capacity, MGD	2014 Albuquerque Dollars, US$	Source
RO Facilities			
Horizon Regional MUD (TX)	6	12,045,815	(Shirazi and Arroyo, 2010)
Kay Bailey Hutchison Brackish Groundwater Desalination Plant (TX)	27.5	128,171,186	(Arroyo and Shirazi, 2012)
Lake Granbury Surface Water Advanced Treatment System (TX)	12.5	56,508,647	(Shirazi and Arroyo, 2010)
Southmost Regional Water Authority (TX)	7.5	36,269,132	(Arroyo and Shirazi, 2012)
City of Fort Stockton	6.5	11,981,274	(Shirazi and Arroyo, 2010)
WateReuse IT^{3}PR RO Output	25	139,069,525	(Trussell et al., 2015a)
Treatment Scheme 2 (25 MGD capacity)	25	107,360,440	(Texas Water Development Board, 2015)
Orange County Groundwater Replenishment System (CA)	120	392,656,592	(Raucher and Tchobanoglous, 2014)
Cost Estimation Manual-RO Capital Costs Equation	25	126,773,869	(McGivney and Kawamura, 2008)
B: (MF-RO-UVAOP)	20	111,302,400	(Schimmoller, Kealy and Foster, 2015)
Scenario 1C (MF/RO/CL) 20 MGD	20	93,327,062	(Water Reuse Research Foundation, 2014)
Scenario 1C (MF/RO/CL) 70 MGD	70	289,543,918	(Water Reuse Research Foundation, 2014)
Scenario 2B (MF/RO/UV) 20 MGD	20	111,061,245	(Water Reuse Research Foundation, 2014)
Scenario 2B (MF/RO/UV) 70 MGD	70	331,903,757	(Water Reuse Research Foundation, 2014)
Alternative A-27 (NM)	8.9	95,731,158	(New Mexico Office of the State Engineer and the Interstate Stream Commission, 2004)
Alternative A-39 (NM)	20	130,356,075	(New Mexico Office of the State Engineer and the Interstate Stream Commission, 2004)
O_3/BAC Facilities			

WateReuse IT3PR O_3/BAC Output	25	89,828,154	(Trussell et al., 2015a)
Treatment Scheme 6 (25 MGD capacity)	25	32,926,960	(Texas Water Development Board, 2015)
Cost Estimation Manual BAC Capital Equation	25	65,850,433	(McGivney and Kawamura, 2008)
Pre-design Cost Estimate for a Conventional Treatment Plant with Ozone GAC Filters	100	227,220,602	(McGivney and Kawamura, 2008)
A: (Coag-Sed-03-BAC-GAC-UV)	20	84,404,320	(Schimmoller, Kealy and Foster, 2015)
Scenario 2A (O_3/GAC) 20 MGD	20	83,643,754	(Water Reuse Research Foundation, 2014)
Scenario 2A (O_3/GAC) 70 MGD	70	193,944,432	(Water Reuse Research Foundation, 2014)
Water Rights Costs			
Description	**Cost per Acre Foot**	**Total Reported Cost**	**Source**
Estimated cost of purchasing 2,762 acre feet of water rights in the Middle Rio Grande basin above Isleta Dam	16,321	45,078,602	(Payne and Smith, 2011)

APPENDIX D: O&M Costs for Full Advanced Treatment Facilities.*

Facility Name	Capacity, MGD	2014 Albuquerque Dollars, US$	Source
RO Facilities			
Kay Bailey Hutchison Desalination Plant (TX)	15	4,402,706	(Shirazi and Arroyo, 2010)
Southmost Regional Water Authority (TX)	6	3,142,855	(Shirazi and Arroyo, 2010)
West Basin (CA)	12.5	10,189,778	(National Research Council, 2012)
Treatment Scheme 2 (25 MGD capacity)	25	13,975,731	(Texas Water Development Board, 2015)
Orange County Groundwater Replenishment System With Expansion (CA)	120	34,495,512	(Raucher and Tchobanoglous, 2014)
Orange County Groundwater Replenishment System Original (CA)	68	23,210,513	(Water Reuse Research Foundation, 2014)
B: (MF-RO-UVAOP)	20	5,192,000	(Schimmoller, Kealy and Foster, 2015)
Scenario 1C (MF/RO/CL) 20 MGD	20	5,061,857	(Water Reuse Research Foundation, 2014)
Scenario 1C (MF/RO/CL) 70 MGD	70	16,715,252	(Water Reuse Research Foundation, 2014)
Scenario 2B (MF/RO/UV) 20 MGD	20	5,472,553	(Water Reuse Research Foundation, 2014)
Scenario 2B (MF/RO/UV) 70 MGD	70	18,096,602	(Water Reuse Research Foundation, 2014)
O_3/BAC Facilities			
Treatment Scheme 6 (25 MGD capacity)	25	2,387,231	(Texas Water Development Board, 2015)
Cost Estimation Manual BAC O&M Equation	25	2,050,408	(McGivney and Kawamura, 2008)
Millard H. Robbins, Jr. Regional Water Reclamation Facility (VA)	31.5	6,463,841	(Water Reuse Research Foundation, 2014)
A: (Coag-Sed-03-BAC-GAC-UV)	20	3,696,000	(Schimmoller, Kealy and Foster, 2015)
Scenario 2A (O_3/GAC) 20 MGD	20	3,381,988	(Water Reuse Research Foundation, 2014)
Scenario 2A (O_3/GAC) 70 MGD	70	10,405,546	(Water Reuse Research Foundation, 2014)

*It was assumed that UV lamps would be replaced annually; this is included in the O&M costs for the UV systems.

APPENDIX E: Calculation Methods for Determining Additional Infrastructure Capital Costs.

Piece of infrastructure	Equations and Calculation Methods	Source
Concrete pipe of 42 inch diameter (Flow path *a*) *L*=Length of installation *D*=Diameter of pipe d_{exc}=Depth of excavation	Base installed price for concrete pipe: $P_{base} = (11.7 + 0.51D^{1.38})L$ Trenching and excavation cost: $p_{trench} = (2.9 + 0.0018D^{1.9} + 0.13{d_{exc}}^{1.77})L$ Embedment cost: $p_{embed} = (1.6 + 0.0062\,D^{1.83})L$ Backfill and compaction cost: $p_{fill} = (-0.094 - 0.062D^{0.73} + 0.18{d_{exc}}^{2.03} + 0.02Dd_{exc})L$ Valves, fittings and hydrants cost: $p_{fit} = (9.8 + 0.02\,D^{1.8})L$ Total piping cost: $p_{total} = (p_{base} + p_{trench} + p_{embed} + p_{fill} + p_{fit})$	(Woods et al., 2013)
	$405 per foot	(CDM, 2004)
	$630 per foot	(Davis, 2009)
	$1,437,500 per mile	(New Mexico Office of the State Engineer and the Interstate Stream Commission, 2004)
Ductile iron pipe of 42 inch diameter (Flow path *b*)	Base installed price for ductile iron pipe: $p_{base} = (-44 + 0.33D^{1.72} + 2.87 * 50^{0.74})L$ *See "Concrete pipe of 42 inch diameter" above for the remainder of equations.	(Woods et al., 2013)
	$405 per foot	(CDM, 2004)
	$630 per foot	(Davis, 2009)
	$1,437,500 per mile	(New Mexico Office of the State Engineer and the Interstate Stream Commission, 2004)
Concrete pipe of 16 inch diameter (Flow path *c*)	Based installed price for concrete pipe: $P_{base} = (11.7 + 0.51D^{1.38})L$	(Woods et al., 2013)

	*See "Concrete pipe of 42 inch diameter" above for the remainder of equations.	
Concrete pipe of 16 inch diameter (Flow path *c*)	$130 per foot	(CDM, 2004)
	$240 per foot	(Davis, 2009)
	$140,070 per mile	(New Mexico Office of the State Engineer and the Interstate Stream Commission, 2004)
Pumping for path *a*	$0.15 per gallon per day (25 MGD)	(Woods et al., 2013)
	188,888(25MGD)+140,743	(McGivney and Kawamura, 2008)
Pumping for path *b*	$0.15 per gallon per day (25 MGD)	(Woods et al., 2013)
	188,888(25MGD)+140,743	(McGivney and Kawamura, 2008)
Pumping for path *c*	$0.15 per gallon per day (3.045 MGD)	(Woods et al., 2013)
	188,888(4.035MGD)+140,743	(McGivney and Kawamura, 2008)
ASR wells and pumps	29 wells (610 gpm each) at $2,324,655 each	(Daniel B. Stephenson and Associates, Inc., 2010)
	12 wells (1400 gpm each) at $5,197,879 each	(Daniel B. Stephenson and Associates, Inc., 2010)
Brine disposal (wells only for 3.045 MGD)	6 wells (385 gpm each) at $2,050,000 each	(Daniel B. Stephenson and Associates, Inc., 2014)
	4 wells (610 gpm each) at $2,050,000 each	(Daniel B. Stephenson and Associates, Inc., 2014)
	5 wells (435 gpm each) at $2,625,000 each	(Universal Asset Management, 2011)
	3 wells (870 gpm each) at $2,625,000 each	(Universal Asset Management, 2011)
Engineered Storage	170% of average daily reclaimed water production	(Woods et al., 2013)
	50% of average daily delivered water	(Arroyo and Shirazi, 2012)
	$0.20 per gallon	(Boyer et al., 2010)
	$0.50 per gallon	(Arroyo and Shirazi, 2012)
	$0.80 per gallon	(Woods et al., 2013; Davis et al., 2009)
UV for O_3/BAC	25MGD output from IT^3PR toolkit	(Trussell et al., 2015a)
UV for RO	25MGD output from IT^3PR toolkit	(Trussell et al., 2015a)
Ozone	25MGD output from IT^3PR toolkit	(Trussell et al., 2015a)
RO membranes	20% of 4248 membranes (850) replaced annually	(Dow Water and Process Solutions, 2016)

APPENDIX F: Calculation Methods for Additional Infrastructure O&M Costs.

Piece of additional infrastructure	Calculation Method	Source
Piping for path *a*	$3,200 per mile per year	(Woods et al., 2013)
Piping for path *b*	$3,200 per mile per year	(Woods et al., 2013)
Piping for path *c*	$3,200 per mile per year	(Woods et al., 2013)
Pumping for path *a*	Table B-2. Headworks 20MGD + 5MGD	(Davis, 2009)
Pumping for path *b*	Table B-2. Headworks 20MGD + 5MGD	(Davis, 2009)
Pumping for path *c*	Table B-2. Headworks 3MGD	(Davis, 2009)
ASR wells and pumps	46 wells (385 gpm each) $3,000 per year each	(Pedregon, 2015)
	29 wells (610 gpm each) $3,000 per year each	(Pedregon, 2015)
Brine disposal (wells only)	6 wells (385 gpm each) $3,000 per year each	(Pedregon, 2015)
	4 wells (610 gpm each) $3,000 per year each	(Pedregon, 2015)
Engineered Storage	1% of capital costs for 12.5MG of storage at $0.50 per gallon	(Arroyo and Shirazi, 2012)
	1% of capital costs for 42 MG of storage at $0.80 per gallon	(Woods et al., 2013)
Drinking Water Treatment Plant	$403 per million gallons treated per year	(Albuquerque Bernalillo County Water Utility Authority, 2014)
Ozone (BAC) equipment replacement cost	$2,700,000 converted to Albuquerque equivalent dollars using ENRI. ($2,376,000)	(LeBrun, 2017)
UV (BAC) equipment replacement cost	$25,200,000 converted to Albuquerque equivalent dollars using ENRI. ($22,176,000)	(DesRochers, 2017)
UV (RO) equipment replacement cost	$3,240,000 converted to Albuquerque equivalent dollars using ENRI. ($3,177,504)	(DesRochers, 2017)

APPENDIX G: Useful Service Life Estimates.

Equipment	Useful Service Life Estimate (years)	Source of Information
Elements Common to Reuse Scenarios with Advanced Treatment		
Elevated Storage Tanks	50	(Texas Commission on Environmental Quality, 2007)
Treatment and Disposal Equipment	25	(Texas Commission on Environmental Quality, 2007)
UV Disinfection Equipment	5[1]	(Texas Commission on Environmental Quality, 2007)
Distribution System	50	(Texas Commission on Environmental Quality, 2007)
Pumping and Equipment	18	(Florida Department of State, 2008)
Water Treatment Equipment	22	(Florida Department of State, 2008)
Pipes	37	(Florida Department of State, 2008)
Cast Iron or Ductile Iron	40	(Florida Department of State, 2008)
RO-related Equipment		
Booster Pumps > 5hp	30	(Texas Commission on Environmental Quality, 2007)
Membrane Elements	5	(Florida Department of State, 2008)
Treatment Process Pumps > 5hp	10	(Texas Commission on Environmental Quality, 2007)
O_3/BAC-related Equipment		
Ozone Disinfection Equipment	5[2]	(Texas Commission on Environmental Quality, 2007)
ASR-related Equipment		
Well Pumps > 5 hp	10	(Texas Commission on Environmental Quality, 2007)
Wells	30	(Texas Commission on Environmental Quality, 2007)

[1]"UV disinfection equipment" was assumed to include reactor chambers, ballasts and remaining treatment equipment. It does not include lamp replacement, which is estimated to be required once per year and included in the O&M costs (see Appendix D). It should be noted that the vendor of UV equipment who was contacted for costs estimated useful life of the UV equipment to be between 20-30 years. The TX CEQ values, referenced above, were used instead because they are unbiased, more conservative, and represent recommendations to utilities to help them anticipate costs.

[2]"Ozone disinfection equipment" was assumed to include ozone generation and cooling equipment as well as any other major mechanical components. The note in footnote #1 about the TX CEQ service life estimates versus vendor estimates also applies here.

APPENDIX H: Present Worth Replacement Cost Breakdown by Scenario At 3% And 8% Discount Rates.

Present Worth Replacement Cost Breakdown, 3% Discount Rate		
Piece of Replaced Infrastructure	**Present Worth of Recurring Capital Cost**	**Project Year Replaced**
Scenario 1		
None	None	N/A
Replacement Present Worth Total	**None**	
Scenario 2A		
Pumping flow path *a*	$817,992	Year 18
Membranes	$2,740,943	Year 5
Membranes	$2,364,361	Year 10
Membranes	$2,039,519	Year 15
Membranes	$0	Year 20
UV (RO)	$2,459,470	Year 5
UV (RO)	$2,121,561	Year 10
UV (RO)	$1,830,077	Year 15
UV (RO)	$0	Year 20
Pumping flow path *b*	$1,369,684	Year 18
Pumping flow path *c*	$1,383,199	Year 18
Pumping flow path *b* (ASR)	$3,475,527	Year 10
Pumping flow path *b* (ASR)	$0	Year 18
Replacement Present Worth Total	**$20,602,333**	
Scenario 2B		
Pumping flow path *a*	$817,992	Year 18
Ozone	$2,049,558	Year 5
Ozone	$1,767,967	Year 10
Ozone	$1,525,064	Year 15
Ozone	$0	Year 20
UV(BAC)	$19,129,212	Year 5
UV(BAC)	$16,501,027	Year 10
UV(BAC)	$14,233,931	Year 15
UV(BAC)	$0	Year 20
Pumping flow path *b*	$1,369,684	Year 18
Pumping flow path *b* (ASR)	$3,475,527	Year 10
Pumping flow path *b* (ASR)	$0	Year 20
Replacement Present Worth Total	**$60,869,962**	
Scenario 3A		
Pumping flow path *a*	$817,992	Year 18
Membranes	$2,740,943	Year 5
Membranes	$2,364,361	Year 10
Membranes	$2,039,519	Year 15

Membranes	$0	Year 20
UV (RO)	$2,459,470	Year 5
UV (RO)	$2,121,561	Year 10
UV (RO)	$1,830,077	Year 15
UV (RO)	$0	Year 20
Pumping flow path *b*	$1,369,684	Year 18
Pumping flow path *c*	$1,383,199	Year 18
Replacement Present Worth Total	**$17,126,806**	
Scenario 3B		
Pumping flow path *a*	$817,992	Year 18
Ozone	$2,049,558	Year 5
Ozone	$1,767,967	Year 10
Ozone	$1,525,064	Year 15
Ozone	$0	Year 20
UV(BAC)	$19,129,212	Year 5
UV(BAC)	$16,501,027	Year 10
UV(BAC)	$14,233,931	Year 15
UV(BAC)	$0	Year 20
Pumping flow path *b*	$1,369,684	Year 18
Replacement Present Worth Total	**$57,394,435**	
Scenario 4A		
Pumping flow path *a*	$817,992	Year 18
Membranes	$2,740,943	Year 5
Membranes	$2,364,361	Year 10
Membranes	$2,039,519	Year 15
Membranes	$0	Year 20
UV (RO)	$2,456,470	Year 5
UV (RO)	$2,121,561	Year 10
UV (RO)	$1,830,077	Year 15
UV (RO)	$0	Year 20
Pumping flow path *b*	$1,369,684	Year 18
Pumping flow path *c*	$1,383,199	Year 18
Replacement Present Worth Total	**$17,126,806**	
Scenario 4B		
Pumping flow path *a*	$817,992	Year 18
Ozone	$2,049,558	Year 5
Ozone	$1,767,967	Year 10
Ozone	$1,525,064	Year 15
Ozone	$0	Year 20
UV(BAC)	$19,129,212	Year 5
UV(BAC)	$16,501,027	Year 10
UV(BAC)	$14,233,931	Year 15
UV(BAC)	$0	Year 20

Pumping flow path *b*	$1,369,684	Year 18
Replacement Present Worth Total	**$57,394,435**	
Present Worth Replacement Cost Breakdown, 8% Discount Rate		
Piece of Replaced Infrastructure	**Present Worth of Recurring Capital Cost**	**Project Year Replaced**
Scenario 1		
None	None	N/A
Replacement Present Worth Total	**None**	
Scenario 2A		
Pumping flow path *a*	$511,378	Year 18
Membranes	$2,162,556	Year 5
Membranes	$1,471,799	Year 10
Membranes	$1,001,682	Year 15
Membranes	$0	Year 20
UV (RO)	$1,940,479	Year 5
UV (RO)	$1,320,657	Year 10
UV (RO)	$898,817	Year 15
UV (RO)	$0	Year 20
Pumping flow path *b*	$856,276	Year 18
Pumping flow path *c*	$864,725	Year 18
Pumping flow path *b* (ASR)	$2,163,493	Year 10
Pumping flow path *b* (ASR)	$0	Year 18
Replacement Present Worth Total	**$13,191,861**	
Scenario 2B		
Pumping flow path *a*	$511,378	Year 18
Ozone	$1,617,066	Year 5
Ozone	$1,100,548	Year 10
Ozone	$749,014	Year 15
Ozone	$0	Year 20
UV(BAC)	$15,092,613	Year 5
UV(BAC)	$10,271,779	Year 10
UV(BAC)	$6,990,800	Year 15
UV(BAC)	$0	Year 20
Pumping flow path *b*	$856,276	Year 18
Pumping flow path *b* (ASR)	$2,163,493	Year 10
Pumping flow path *b* (ASR)	$0	Year 20
Replacement Present Worth Total	**$39,352,966**	
Scenario 3A		
Pumping flow path *a*	$511,378	Year 18
Membranes	$2,162,556	Year 5
Membranes	$1,471,799	Year 10
Membranes	$1,001,682	Year 15
Membranes	$0	Year 20

UV (RO)	$1,940,479	Year 5
UV (RO)	$1,320,657	Year 10
UV (RO)	$898,817	Year 15
UV (RO)	$0	Year 20
Pumping flow path *b*	$856,276	Year 18
Pumping flow path *c*	$864,725	Year 18
Replacement Present Worth Total	**$11,028,369**	
Scenario 3B		
Pumping flow path *a*	$511,378	Year 18
Ozone	$1,617,066	Year 5
Ozone	$1,100,548	Year 10
Ozone	$749,014	Year 15
Ozone	$0	Year 20
UV(BAC)	$15,092,613	Year 5
UV(BAC)	$10,271,779	Year 10
UV(BAC)	$6,990,800	Year 15
UV(BAC)	$0	Year 20
Pumping flow path *b*	$856,276	Year 18
Replacement Present Worth Total	**$37,189,473**	
Scenario 4A		
Pumping flow path *a*	$511,378	Year 18
Membranes	$2,162,556	Year 5
Membranes	$1,471,799	Year 10
Membranes	$1,001,682	Year 15
Membranes	$0	Year 20
UV (RO)	$1,940,479	Year 5
UV (RO)	$1,320,657	Year 10
UV (RO)	$898,817	Year 15
UV (RO)	$0	Year 20
Pumping flow path *b*	$856,276	Year 18
Pumping flow path *c*	$864,725	Year 18
Replacement Present Worth Total	**$11,028,369**	
Scenario 4B		
Pumping flow path *a*	$511,378	Year 18
Ozone	$1,617,066	Year 5
Ozone	$1,100,548	Year 10
Ozone	$749,014	Year 15
Ozone	$0	Year 20
UV(BAC)	$15,092,613	Year 5
UV(BAC)	$10,271,779	Year 10
UV(BAC)	$6,990,800	Year 15
UV(BAC)	$0	Year 20
Pumping flow path *b*	$856,276	Year 18
Replacement Present Worth Total	**$37,189,473**	

APPENDIX I: Sensitivity Analysis on Discount Rate Ranging from 3 to 8%.

Discount rates ranging from 3 to 8 percent were examined. This appendix shows results of a sensitivity analysis performed for the 3 to 8 percent range of discount rates. As can be seen in Figure I1, the total present worth values for Scenarios 2-4 follow the same pattern at all discount rates examined. Figures I2 through I4 illustrate how the total present worth changes with discount rate.

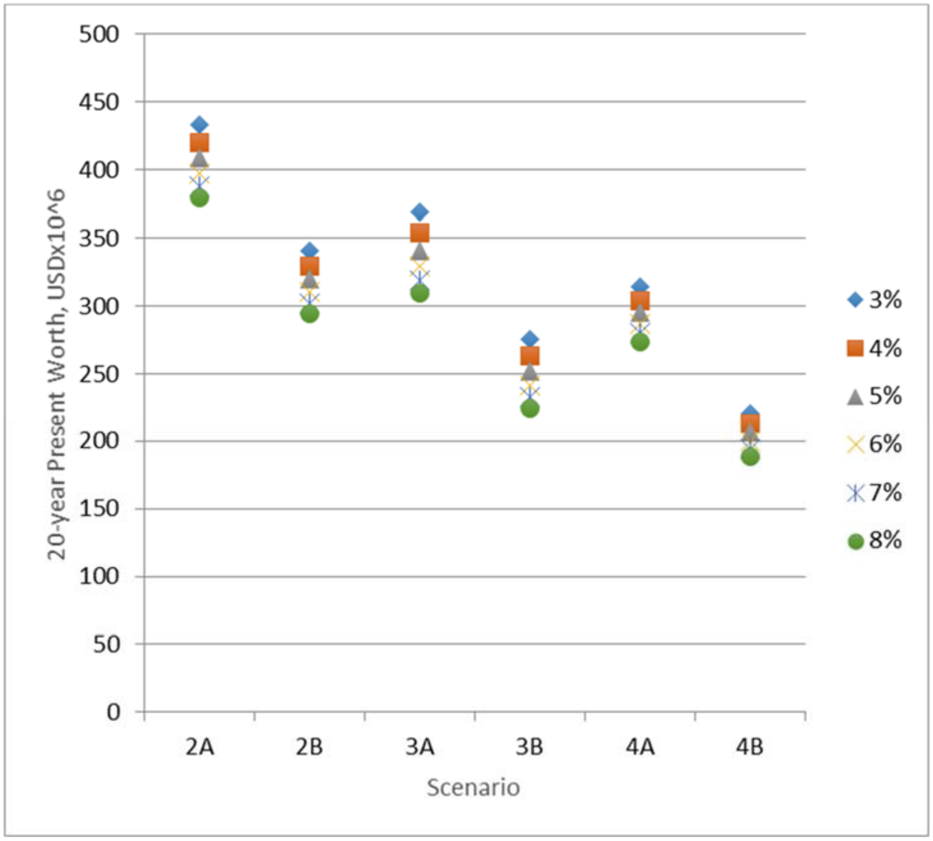


Figure I1. Total Present Worth of Scenarios 2-4 over a Range of Discount Rates.

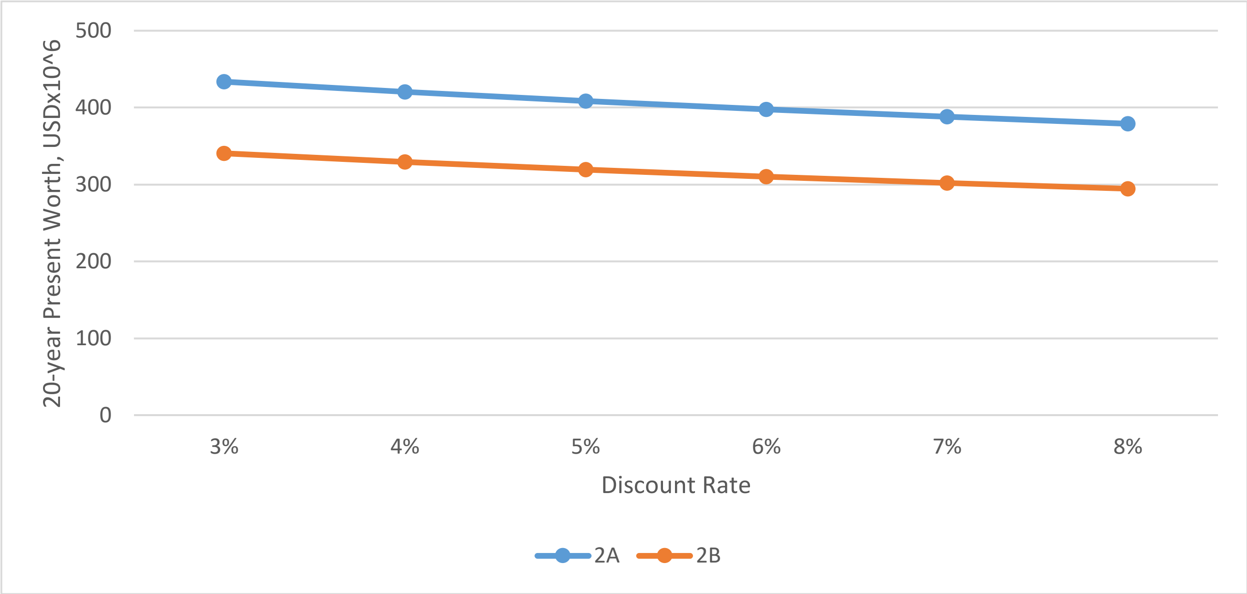


Figure I2. Scenario 2: Total Present Worth Sensitivity to Discount Rate.

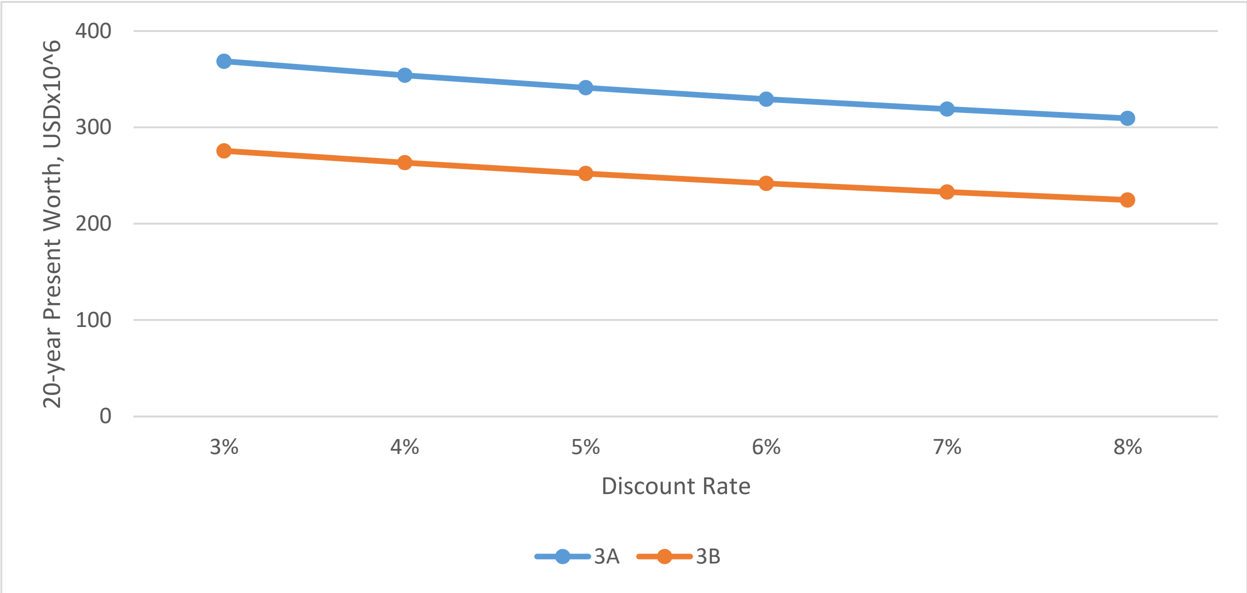


Figure I3. Scenario 3: Total Present Worth Sensitivity to Discount Rate.

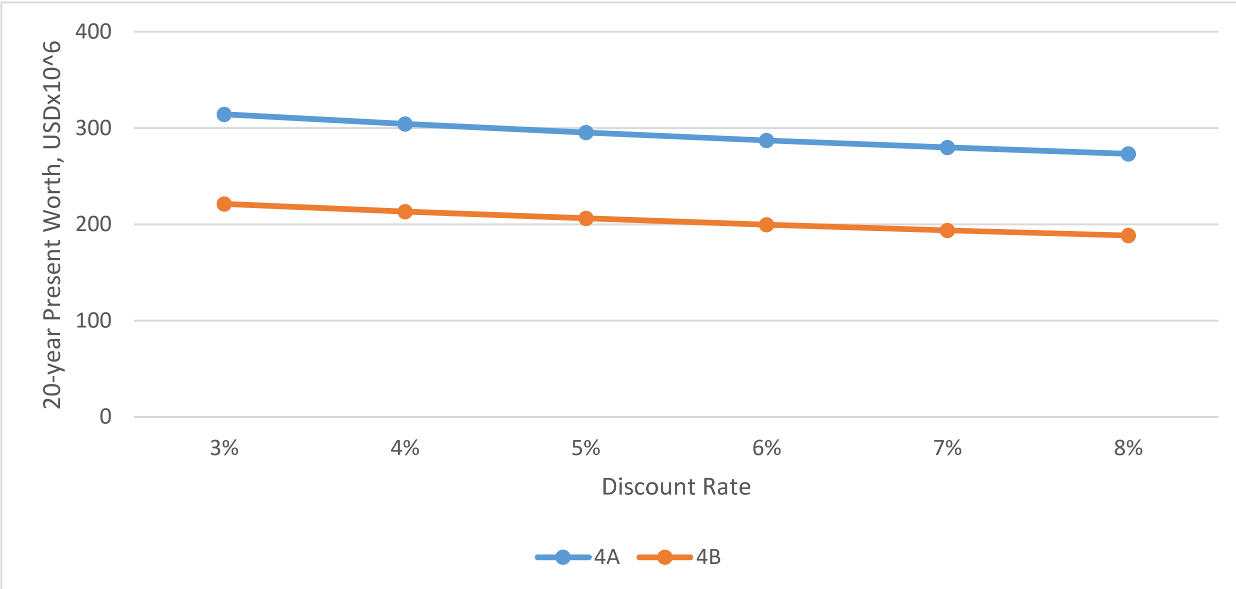


Figure I4. Scenario 4: Total Present Worth Sensitivity to Discount Rate.