EVALUATING NANOFILTRATION, REVERSE OSMOSIS, AND ION EXCHANGE TO MEET CONSUMPTIVE USE CONSTRAINTS AND FINISHED WATER QUALITY GOALS FOR BROWARD COUNTY

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Introduction

In June 2002, the Broward County Office of Environmental Services (BCOES) hired CDM to provide design, bidding, and construction management services for a nanofiltration (NF) process addition to the County's Water Treatment Plant 1A (WTP 1A), a 16 mgd lime softening facility. The primary objective of the project was to maintain continued compliance with the Disinfectant/Disinfection By-product (D/DBP) Rule and improve the aesthetic quality (color) of the finished water. In characterizing the existing lime softening process during the preliminary design phase, it was found that the existing process is capable of meeting all of the finished water quality goals established by the County for the project, with the exception of color. In light of this fact, the County requested that CDM prepare a treatment process alternative analysis comparing the nanofiltration (NF) process with anion exchange for color removal.

The preliminary design phase also included a review of the County's existing South Florida Water Management District (SFWMD) Water Use Permit (WUP) for the WTP 1A system and evaluation of the advisability of providing a portion of the desired treatment capacity with reverse osmosis (RO) trains utilizing a Floridan aquifer raw water supply. Population and water demand projections were provided by the County for use in the analysis. A key factor in the analysis was the future SFWMD WUP raw water allocation expected to be available from the Biscayne aquifer, since future demands in excess of the Biscayne aquifer allocation must be met with a Floridan aquifer raw water supply and RO process. Two scenarios were considered. The first assumed that future Biscayne aquifer allocations would be limited to the levels in the existing WUP. The second scenario assumed that future raw water allocations from the Biscayne aquifer under the SFWMD WUP would be equal to the allocations in the existing permit, plus an additional 4.33 mgd in the form of credits for reclaimed water reuse and conservation.

Scope of Analysis

Based on the above-mentioned scenarios for future SFWMD WUP allocations and the demand projections provided by the County, the following tasks were identified for the analysis:

1. Prepare a preliminary layout and opinion of cost for RO process improvements necessary to meet raw water supply constraints and finished water quality goals under the assumption that allocations in the existing SFWMD WUP can not be increased in the future.
2. Prepare a 20-year present worth comparison of the following two alternatives under the assumption that WUP allocations may be increased by the above-noted 4.33 mgd credit:
    - Lime softening process combined with anion exchange to meet water quality goals
    - Lime softening process combined with nanofiltration to meet water quality goals.

Data and Assumptions for Analysis

Assumptions

The following assumptions were made for the treatment process alternative analysis:

- Process design criteria are based on meeting the finished water quality goals established during preliminary design, of which the current driver is finished water color. The finished water quality goal for color is 7 CU at maximum day demand (MDD).
- With respect to operating costs for the existing lime softening process, only those costs that vary depending on which additional process is selected were evaluated (i.e., the marginal costs).
- Maintenance and repair and replacement costs for the existing lime softening process equipment are based on the County's existing capital improvements program.

Historical and Projected Water Demands

Table 1 reflects the water demand projections provided by the County based on the Year 2000 Census. The finished water annual average daily demand (AADD) projections provided in the County projections were adjusted using a maximum day demand to annual average daily demand (MDD/AADD) peak factor of 1.35, which was estimated based on a review of the WTP 1A system demand patterns.

SFWMD Water Use Permit Allocations

The current WUP for the WTP 1A system (Permit No. 06-00146-W) was amended on March 8, 2002, and expires on December 13, 2006. The amended permit sets forth the following withdrawal allocations from the Biscayne aquifer:

- The annual allocation shall not exceed 3,573 million gallons (MG). This equates to a raw water AADD of 9.79 mgd. Under a March 8, 2002 addendum, this annual allocation is increased to 3,840 MG (10.52 mgd AADD), taking effect "upon completion and commencement of operation of the proposed membrane softening plant."
- The maximum daily allocation shall not exceed 12.43 MG (or a raw water MDD of 12.43 mgd).
- An additional maximum daily allocation of "up to 13.68 mgd for a period of time not to exceed 7 days in a 1-year period of time." This means that the County may have a daily demand that falls between 12.43 mgd and 13.68 mgd, no more than seven times a year.

For the comparison of anion exchange to NF, it was assumed that the County may be able to obtain future increases in Biscayne aquifer allocations under the SFWMD WUP. This is based on anticipated credits of 3.70 mgd for reclaimed water reuse and 0.63 mgd for conservation.

Anion Exchange Process Performance

The BCOES WTP 1A utilizes a lime softening process with multimedia gravity sand filtration and chloramination to treat a highly colored Biscayne aquifer raw water supply. The anion exchange system would be located directly downstream of the gravity sand filters and upstream of the clearwell(s) and finished water storage. From a process perspective, this location is appropriate for the anion exchange system to avoid excessive solids loading on the resin from sand, silt, and carbonate precipitate from the lime softeners. Also, the organics loading is marginally reduced by removal mechanisms in the lime softeners.

Several sources of data were reviewed to estimate the color removal efficiency to be expected from the anion exchange process for the purpose of sizing the system for comparison to NF. A pilot testing report entitled *Anion Exchange Feasibility Study at Water Treatment Plant 1A* prepared by CH2M Hill in 1996 noted typical color removal from 17 CU to less than 3 CU during the 1996 pilot testing conducted at WTP 1A.

CDM also contacted the major anion exchange system manufacturers for estimates of process performance with respect to color removal. With a feed water quality typical of lime softened Biscayne aquifer water, and given the typical design resin bed loading rates, they generally expect the process to consistently reduce the color to below 3 CU. There is no apparent direct relationship between feed water color and treated water color under these conditions (i.e., the performance should not be estimated based on a "percent removal efficiency"). This is consistent with the data reflected in the pilot testing conducted by CH2M Hill at WTP 1A in 1996 and data from the nearby City of Pembroke Pines water treatment plant, which uses anion exchange for color removal on a Biscayne aquifer raw water supply. Therefore, sizing of the anion exchange process with respect to the finished water color goal in this analysis is based on an assumed treated water color of 3 CU.

Reverse Osmosis Process Performance

A reverse osmosis treatment process addition at WTP 1A would be supplied by Floridan aquifer raw water wells. Typically, the raw water color in Floridan supply wells in South Florida is very low. The reverse osmosis membranes will remove essentially all the color. Therefore, sizing of the RO process with respect to the finished water color goal is based on an assumed RO permeate color of 0 CU.

Nanofiltration Process Performance

Extensive pilot testing of the NF process was conducted at WTP 1A using the existing Biscayne aquifer raw water supply during the preliminary design phase of the project. The pilot testing results indicate that a NF permeate color of 2 CU or less can be consistently achieved with the WTP 1A raw water supply. Therefore, sizing of the NF process with respect to the finished water color goal is based on an assumed NF permeate color of 2 CU.

Finished Water Quality Goals

As noted above, treatment process characterization efforts conducted during preliminary design indicate that the existing lime softening process is currently meeting all of the finished water quality goals set by the County for the project with the exception of color (the finished water goal for color is 7 CU). Therefore, color is the primary driver with respect to water quality in evaluating and sizing the treatment process addition alternatives addressed in this analysis. The alternatives presented in the following sections are sized to produce a finished water color of 7 CU or less when blended with the lime softened process flow to meet the projected maximum day demand for each study year.

Preliminary Blending Analysis

Table 1 presents a preliminary blending analysis for each of the three treatment process alternatives over the study period. Based on existing process water quality data, it is assumed that the lime softening process will produce a finished water color of 13 CU. The assumed performance with respect to color for the alternative processes are discussed above. The process design capacities listed in Table 1 for each alternative are estimated based on a weighted average of lime process flow blended with the alternative process flow to achieve the finished water color goal at the projected MDD for each study year. It should be pointed out that, in previous pilot testing programs, CDM has noted that color is not an additive property. However, a weighted average calculation is generally a conservative estimation of the blended product water color. Also, note that the anion exchange capacity is provided in 1.5 mgd units (pressure vessels) and the NF and RO membrane capacity is provided in 2.0 mgd units (skids), in accordance with the assumptions outlined above.

Table 1. Estimate of Alternative Process Design Capacity Based on Finished Water Color of 7 Color Units

		Anion Exchange		Nanofiltration				Reverse Osmosis			
Year	MDD (mgd)	Capacity (mgd)	No. of Units	Capacity (mgd)	No. of Units	Inst Cap (mgd)	LS flow (mgd)	Capacity (mgd)	No. of Units	Inst Cap (mgd)	LS flow (mgd)
2005	12.29	7.4	5	6.7	4	8.0	4.29	5.7	3	6.0	6.29
2008	13.10	7.9	6	7.1	4	8.0	5.10	6.0	4	8.0	5.10
2010	13.64	8.2	6	7.4	4	8.0	5.64	6.3	4	8.0	5.64
2015	14.85	8.9	6	8.1	5	10.0	4.85	6.9	4	8.0	6.85
2020	16.07	9.6	6	8.8	5	10.0	6.07	7.4	4	8.0	8.07
2025	16.74	10.0	6	9.1	5	10.0	6.74	7.7	4	8.0	8.74

Process Improvements Layouts

Anion Exchange Process

Figure 1 depicts a schematic of WTP 1A showing the proposed location of the anion exchange system in the overall treatment process. The anion exchange process will treat a sidestream taken from the dual media filter effluent, which will then be blended back into the balance of the treated water stream prior to pumping to distribution. Filtered water would be drawn from a tie-in to the existing equalization line between the east and west clearwells, pumped through the ion exchange columns using four new feed pumps, and then discharged into the east clearwell. This blending point is the same as has been proposed for the NF process in the previously developed preliminary design for the NF improvements, and would be the same blending point for an RO process. The same clearwell improvements and any necessary improvements to the transfer pumping system would be proposed under all three process alternatives. Therefore, these improvements are common to all alternatives and will not be considered in the cost comparison. Waste backwash water and resin regeneration water will amount to approximately 0.25 to 0.3% of the treated water stream, or approximately 22,500 to 27,000 gallons per day at a treated water flow of 9.0 mgd. This can be disposed of in the onsite wastewater pump station to be pumped to the wastewater treatment plant.

The ion exchange system will include six 12-foot diameter, 1.5 mgd vessels to meet the County’s finished water color goal, as determined in Table 1. In addition, a backwash and clean-in-place system will be provided adjacent to the columns.

Reverse Osmosis Process

Figure 2 depicts a schematic of WTP 1A showing the proposed location of the RO or NF addition in the overall treatment process (the process configuration relative to the lime softening process stream would be substantially the same for the RO and NF alternatives). The RO process would consist of four Floridan aquifer raw water supply wells and well pumps, raw water transmission piping, four cartridge filters, acid, antiscalant, and caustic storage and feed systems, four 2-mgd membrane skids

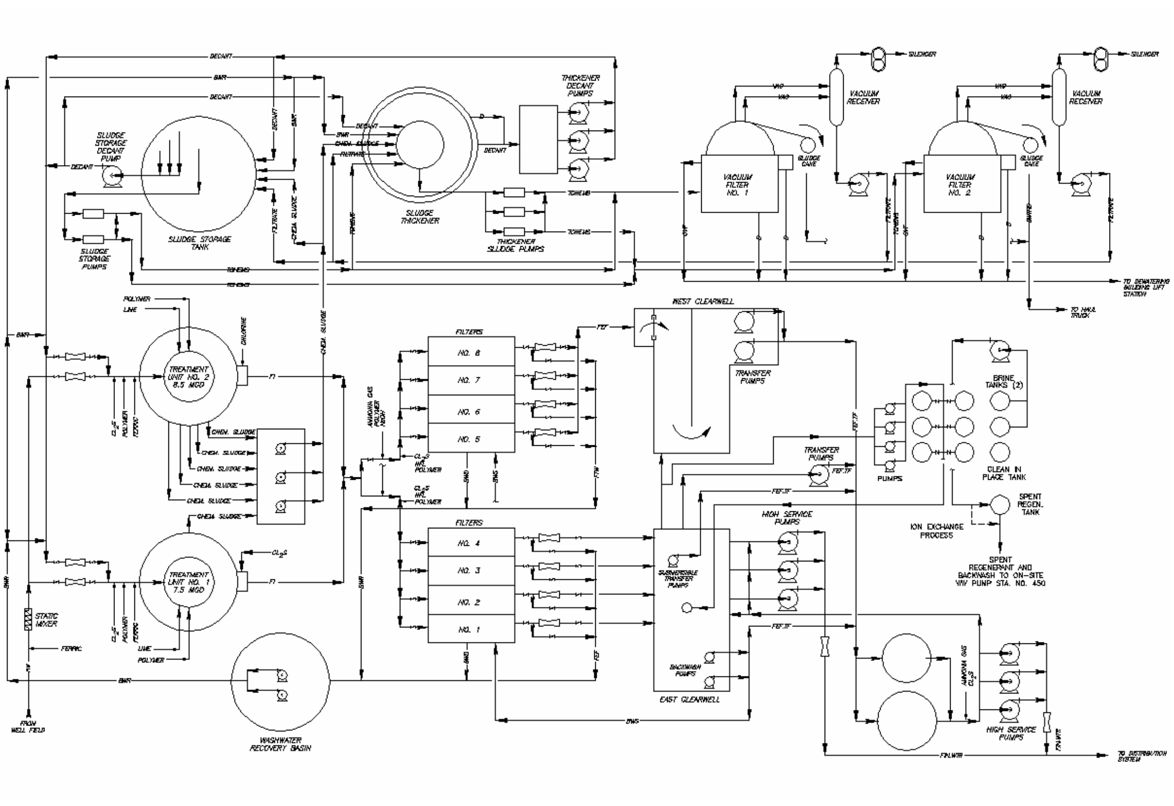

Figure 1. Anion Exchange Process Schematic

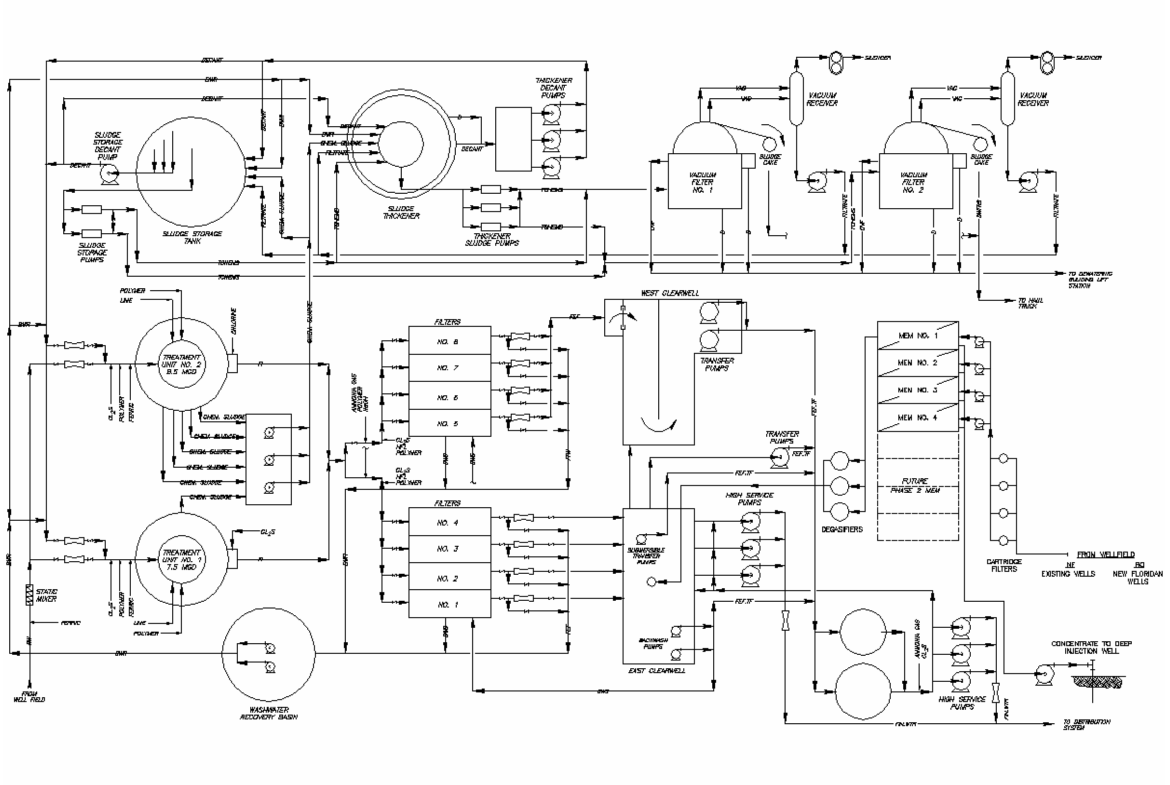

Figure 2. Reverse Osmosis and Nanofiltration Process Schematic

with dedicated membrane feed pumps, a membrane cleaning system, four degasifiers, and associated electrical and control equipment. The design recovery rate for the RO process would be 80%. The operating feed pressure to the RO membranes would be approximately 260 to 310 psi, depending on the selected membrane and degree of fouling. Concentrate will be disposed of in a deep injection well located on site, in the northwest corner of the site. The permeate would be blended with the lime softened water in the east clearwell prior to pumping to distribution.

Nanofiltration Process

Figure 2 also shows the process schematic for the NF process alternative. The improvements for the NF alternative would be very similar to the RO process with several exceptions. The NF process would consist of four cartridge filters, acid, antiscalant, and caustic storage and feed systems, four 2-mgd membrane skids with dedicated membrane feed pumps, a membrane cleaning system, four degasifiers, and associated electrical and control equipment. The raw water supply for the NF process would be from the existing Biscayne aquifer wellfield. Raw water transmission piping improvements would be made to dedicate existing wells 4, 5, 6 and 7 to the NF process. New, higher head pumps would be installed in these wells. Wells 1, 2, 3, 8, and 9 would be dedicated to the lime softening process.

The design recovery rate for the NF process would be 85%. The operating feed pressure to the NF membranes would be approximately 90 to 120 psi. Also, it was determined during the NF pilot testing that the process could be operated without acid or antiscalant. These differences between the RO and NF process designs and operating requirements are reflected in the opinions of cost.

Evaluation of Maintaining Lime Softening Capacity

Since the anion exchange system constitutes an additional step to the overall lime softening process, whereas the NF process effectively replaces lime softening process capacity, the cost differences for operating and maintaining certain lime softening process equipment must be considered in comparing the two alternatives.

Column 2 of Table 1 presents the projected total MDD for WTP 1A for each study year, all of which must be treated by the lime process under the anion exchange alternative. Column 8 of Table 1 presents the required flow from the lime softening process under MDD conditions for each study year for the NF process alternative. This reduction in treated flow through the lime process under the NF alternative must be considered in the 20-year present worth analysis.

The lime softening-related costs to be considered in the present worth comparison can be divided into fixed and variable operating costs, periodic maintenance costs, and renewal and replacement (R&R) costs. Costs associated with maintaining equipment in service and available for use (e.g., fixed operating costs, periodic maintenance, and R&R) should be based on the required process capacity to meet MDD. This is represented by column 2 for the anion exchange alternative and column 8 for the NF alternative. Since the MDD to be treated by the lime process under the NF alternative never exceeds 6.74 mgd (column 8), this allows certain lime softening equipment to be taken out of service under the

NF alternative. This equipment may be kept available on site for back-up use, but should not require R&R or incur significant maintenance expenses. The equipment that may be taken out of service includes one lime softening unit, one lime slaker, one bank of granular media filters, and one vacuum filter.

Costs that vary with the treated flow rate (i.e., variable costs such as treatment chemical use, lime sludge hauling, and electricity) were based on the incremental flow adjusted to the annual average daily demand.

The marginal operation and maintenance cost estimates associated with the existing lime softening process were provided by the County. These costs were incorporated into the present worth analysis as provided by the County, with the following adjustments:

1. The material provided by the County indicated that the County is currently not charged for sludge dumping at the landfill, but included an estimated cost for dumping. After discussion with the County, and considering the County's current and anticipated sludge hauling and disposal contract conditions, it was agreed that no sludge hauling costs would be included until the year 2016. From 2016 through the end of the study period, sludge hauling costs would be based on a unit cost of $20/ton.

2. The periodic maintenance costs provided by the County included costs for all of the lime softening equipment. Since the NF alternative allows one lime softening unit, one lime slaker, one bank of granular media filters, and one vacuum filter to be taken out of service, the costs under the NF alternative were reduced by the following:

   - 50% of the total maintenance costs for all filters (1 through 8)
   - 50% of the total maintenance costs for the lime slakers (1 and 2)
   - 50% of the total maintenance costs for the vacuum filters (1 and 2)
   - 50% of the total maintenance costs for the softening units (1 and 2)

3. The R&R costs provided by the County included costs for all of the lime softening equipment. Since the NF alternative allows the equipment mentioned above to be taken out of service, the costs under the NF alternative were reduced by the following:

   - R&R cost for one lime softening unit ($300,000)
   - R&R cost for one vacuum filter ($60,000)
   - R&R cost for one vacuum filter vac pump ($12,000)
   - R&R cost for one lime slaker ($85,000)
   - R&R cost for 50% of treatment unit and filter electric valve operators ($104,000)

The above-described marginal costs for the lime softening process are reflected in the present worth analysis presented below.

Opinions of Capital and Operation and Maintenance Costs

Anion Exchange Process

Table 2 presents the capital and operation and maintenance (O&M) costs for the anion exchange process improvements. Line item incremental cost “adders” are included for certain system design enhancements desired by the County, which are considered in the present worth analysis. These costs are based on a project-specific quotation from a leading ion exchange system manufacturer, a review of the schedule of values for the City of Pembroke Pines anion exchange process improvements project, the process layout discussed above, and estimates for required general mechanical improvements.

Table 2. Capital and Operation and Maintenance Costs for Anion Exchange Alternative

Description	Cost
Anion exchange system construction:	$3,464,500
<u>Construction Costs for System Enhancements</u>	
1. Access catwalk:	$14,600
2. Air scour system:	$29,200
3. Clean in place system:	$29,200
4. On-line organics monitoring:	$7,800
5. Vessel drain piping upgrade:	$14,600
6. Piping materials upgrade:	$14,600
<u>Annual Operation and Maintenance Costs</u>	
1. Labor (additional):	$50,000
2. Equipment maintenance:	$65,000
3. Chemicals:	$170,000
4. Electricity:	$35,000
5. Other:	$15,000
Annual O&M Cost:	$335,000

Reverse Osmosis and Nanofiltration Processes

Table 3 presents the capital and O&M costs for the NF and RO process improvements. It should be noted that the construction cost for the RO alternative includes the addition of six new Floridan aquifer raw water supply wells, whereas the construction cost for the NF option includes an estimate for the improvements to the existing Biscayne aquifer wellfield recommended in the preliminary design. Both alternatives include the addition of a concentrate disposal deep injection well on the WTP 1A site. The construction cost for the NF alternative includes provisions for expansion from 8.0 to 10.0 mgd during the study period by the addition of a fifth skid (e.g., process building, electrical, yard and process piping, etc.). Also, the construction costs for the RO option reflect process equipment differences related to higher operating pressures (e.g., feed pump horsepower) and different feedwater quality (e.g., strainer sizing). Finally, based on the specific requirements of the BCOES WTP 1A, the construction costs do not include additional incoming switchgear, backup power generator(s), additional high service pumps, finished water storage, improvements to the existing SCADA system, or auxiliary buildings.

Table 3. Capital and Operation and Maintenance Costs for RO and NF Alternatives

Description	RO Costs	NF Costs
Membrane process construction:	$15,981,000	$13,698,000
Annual Operation and Maintenance Costs		
Electricity	$535,000	$223,000
Labor	$50,000	$50,000
Acid	$68,000	$64,000
Antiscalant	$91,000	$86,000
Membrane replacement	$144,000	$144,000
Cleaning chemicals	$25,000	$25,000
Cartridge filter replacement	$10,000	$10,000
Repairs and replacement	$240,000	$205,000
Annual O&M Cost:	$1,163,000	$807,000

Operating cost items for labor, acid, and antiscalant are included under the O&M costs for the NF alternative. These items are included or omitted as "optional" in the high- and low-cost scenarios evaluated in the present worth analyses presented below. They are considered optional due to the fact that the County may operate the NF process with existing staff, and not hire an additional operator, and because previous membrane pilot testing has indicated that the NF system can be operated without acid and antiscalant.

These opinions of cost are based on a review of recent bids and similar construction projects completed by CDM in South Florida, a historical cost database for RO and NF projects maintained by CDM, and the process layouts presented previously.

20-Year Net Present Worth Comparison of Nanofiltration and Anion Exchange

Table 4 presents the results of the present worth analysis. Five separate cost scenarios were considered (three anion exchange scenarios and two NF scenarios). The anion exchange system is base loaded, and the lime softening process treats 100% of the plant flow. R&R costs, labor, equipment maintenance, chemicals, sludge hauling, and electricity for the lime softening plant are based directly on the cost data provided by the County. The variable costs (chemicals, sludge hauling, and electricity) are based on the projected annual ADD. Variable costs for the anion exchange system are based on the base loaded flow rate through the process (process capacity). It should be noted that, while the system layout and cost estimates are based on a modular unit capacity of 1.5 mgd (or 12 ft diameter vessel), the present worth analyses do not include the addition of a seventh 1.5 mgd unit when the required capacity exceeds 9 mgd (in year 2020). CDM evaluated the possibility of rerating the initially installed six vessels based on an increased resin loading rate from 2.30 gpm/ft^3 to 2.56 gpm/ft^3. This represents a 10% increase in loading and is still well within typical design values for this type of system.

The NF process is also base loaded, and the lime softening flow makes up the balance necessary to meet system demands. R&R and equipment maintenance costs for the lime softening process are based on the data provided by the County, adjusted due to the fact that some equipment may be taken out of service. Lime softening operating costs for chemicals, sludge hauling, and electricity are based on the ADD for the lime softening process (reduced by the flow treated by NF). Chemicals and electricity are variable, proportional to the treated flow rate. Replacement membranes and cartridge filters are included.

Table 4. Summary of 20-Year Net Present Worth Comparison

Alternative/Scenario Description	**20-Year Net Present Worth**
Anion exchange, most likely scenario – includes all design enhancements except air scour. Assumes no additional labor costs.	$23,226,000
Anion exchange, low-cost scenario – assumes no design enhancements or additional labor costs.	$23,145,000
Anion exchange, high-cost scenario – includes all design enhancements and one additional plant operator.	$23,999,000
NF, most likely (low-cost) scenario – includes no acid or antiscalant operating costs, and no additional labor costs.	$29,702,000
NF, high-cost scenario – includes operating costs for acid and antiscalant feed, plus one additional plant operator.	$32,915,000

The most likely anion exchange scenario includes all of the system design enhancements listed in Table 2 except for an air scour system, which is considered by the manufacturer to probably not be needed. This scenario also assumes that the improvements will not require additional staff, therefore, no (additional) labor costs are assumed. The low-cost anion exchange scenario is the same as the most likely scenario, except that none of the system design enhancements have been included. The high-cost anion exchange scenario is the same as the most likely scenario, except that the air-scour system has been included, and labor costs assume the addition of one operator with the improvements. The most likely NF scenario assumes that neither acid nor antiscalant will be needed. Also, this scenario assumes that the improvements will not require additional staff. This scenario would also represent the “low-cost scenario” for the NF option. The high-cost NF scenario is the same as the most likely scenario, except that operating (chemical purchase) costs for feeding acid and antiscalant are included, and labor costs assume the addition of one operator with the improvements.

Non-Economic Evaluation Factors

The non-economic evaluation factors are related to the fact that the NF process is basically a “stand-alone” treatment process whereas the anion exchange process is an additional step to the existing plant. NF treats a broader spectrum of contaminants than anion exchange, and offers more assurance that future, more stringent water quality regulations may be met without further process improvements. Also, NF allows for the eventual decommissioning of the entire lime softening process at some time in the future. The NF process also produces a more consistent finished water quality than the anion exchange process since the anion exchange-treated water quality gradually degrades as the resin ages, until the resin is regenerated, cleaned, or ultimately replaced.

Benefits of anion exchange over NF are related to the fact that it is not as dramatic of a change to the process as is NF. An NF plant will likely require more training of the plant operators. Also, the anion exchange system will be much less disruptive to the site and to existing plant operations during construction. Finally, the anion exchange alternative will effectively allow the County to avoid having to make a major commitment at this time to a new process (NF or RO), at a relatively low initial capital cost, until the existing raw water supply availability issues can be better defined.

Conclusion

In reviewing Table 4, the analysis indicates that, under the most likely scenario, the NF alternative is approximately 25% more costly that anion exchange on a 20-year present worth basis. This is primarily a result of the major difference in capital cost between the two alternatives. When comparing the best case with respect to anion exchange, the NF alternative is approximately 35% to 40% more costly than anion exchange. When comparing the best case with respect to NF, the NF is still approximately 20% to 25% more costly than anion exchange on a 20-year present worth basis.

Considering the accuracy range of the opinions of cost, it was concluded that there is a significant difference in the 20-year present worth cost for the two alternatives, with anion exchange being the more cost-effective of the two.