Evaluation of conventional and membrane processes for softening a North Carolina groundwater

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Abstract

Seven alternatives were evaluated to determine the most effective water supply strategy for the United States Marine Corp Air Station at the New River Water Treatment Plant, Camp Lejeune, North Carolina to ensure adequate flow, pressure and quality of potable water. It was determined that the No Action alternative was not acceptable due to plant deficiencies that have caused regulatory compliance violations. In addition, future regulations, particularly those associated with disinfection by-products, indicate that a change in treatment strategy should be made. Two upgrade alternatives and three new facility options were considered to allow reliable compliance with current and future regulatory requirements and produce 3.5 million gallons per day (mgd). All of the new construction options would provide water with a reliable and consistent water quality. To allow alternative costs to be evaluated concurrently with intangible criteria such as reliability and staffing requirements, a system was developed for rating the costs on a scale of 1 to 10. The capital and operational costs for each option were normalized and comparisons made. This paper will review the evaluated treatment options and the methodology used to select the most cost effective option.

Keywords: System evaluation; Softening; Membranes; Groundwater

1. Introduction

The Marine Corps Air Station (MCAS), New River system treats a groundwater source using lime softening and filtration followed by disinfection. The MCAS, New River water system has 23 wells located within the perimeters of Camp Geiger and MCAS, New River. The quality of the raw water supplied to the existing lime softening water treatment plant varies depending on variation in individual well water quality and also which particular wells are in service at any time. The monthly average, maximum, and

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minimum hardness of the raw over the 12-month period ending October 31, 1996 provides a 12-month average hardness of 238 mg/l as CaCO₃ and varied from 202 to 294 mg/l as CaCO₃. Common water treatment practice suggests that this water should be softened to reduce hardness.

2. Discussion

Several alternative actions are available to MCAS, New River in response to the water quality and infrastructure concerns with the existing potable water treatment and distribution system. These include no action, two upgrade options, ion exchange softening, a new lime softening process and membrane softening.

2.1. No Action

This alternative is not feasible as the current water treatment system will not be able to comply with pending regulations.

2.2. Upgrade existing spiractor softening facilities

In this alternative, the existing facilities are rehabilitated and an additional spiractor, sized to average day water demand, is added. The modifications are designed to allow reliable compliance with current and future regulatory requirements.

Fig. 1 is a process flow diagram of the spiractor addition upgrade alternative. Well water enters an equalization tank where it is aerated to oxidize iron and remove hydrogen sulfide and excess carbon dioxide levels. Water is then pumped from the equalization tank to a new 700-gpm spiractor and one or both of the existing rehabilitated 1,200-gpm spiractors, depending on flows. Lime slurry is added to the base of the spiractor to raise the pH to 10. Softened water from the spiractors passes through the existing recarbonation tank outfitted with a liquid carbon dioxide recarbonation system, where pH is adjusted to 8.8 to 9.2. The stabilized water is chlorinated and passes through media filters into the existing clear well. Ammonia is added and finished water pumps transfer the water to the ground storage reservoirs and then to the distribution system.

Implementation of this alternative would provide water quality consistent with water quality goals and regulatory requirements. Reliability would be greater than the existing system; however, due to the inherent reliability issues associated with lime feed systems, this alternative would be less reliable than either ion exchange or membrane alternatives. Operational and maintenance costs, staffing, and spatial requirements are similar to the existing plant. The approximate capital cost of this upgrade alternative is $4,600,000 and approximate annual operational and maintenance costs are $70,000. Based on the capital and operational and maintenance costs, the present value of this alternative is $5,500,000.

2.3. Upgrade with ion exchange facilities

In this alternative, the existing facilities are rehabilitated and the spiractor softening process is replaced by an ion exchange softening process. Chlorine and potassium permanganate are added to complete the oxidation of reduced iron and manganese, and the water is pumped to the existing, rehabilitated filters, where iron, manganese, and particulate material are removed. The water then passes through ion exchange softening columns to remove calcium and magnesium hardness. Since pH is not increased and dissolved inorganic carbon (DIC) is not removed in the ion exchange process, corrosion control is provided through addition of orthophosphate corrosion inhibitor and pH is adjusted with caustic to approximately 7.8, a value consistent with orthophosphate corrosion control and chloramine secondary disinfection.

Implementation of this alternative would provide water quality consistent with water
quality goals and regulatory requirements. Due to the nature of the ion exchange process, the TDS, sodium level, and alkalinity would be greater than lime softening or membrane alternatives.

The reliability of this alternative would be greater than the existing system or the lime softening alternatives due to the removal of the lime feed system. Due to the level of controls, the physical reliability of the ion exchange system is similar to a membrane softening system. Ion exchange does not, however, produce equivalent water quality, with elevated levels of NOM and TDS relative to membrane treatment.

The estimated capital cost of this upgrade alternative is approximately $5,000,000. Operational and maintenance costs would be approximated at $109,000 per year at average production flow of 1.0 mgd. Chemical and power costs are included in O&M costs, and regenerant disposal to sewer with negligible associated cost is assumed. Using these capital and O&M costs, the present value of this alternative is $6,300,000.

2.4. New ion exchange facility

The existing water treatment facility has gone through a prior upgrade, and due to reliability and cost considerations, construction of a new facility could be the best alternative to meet the future water supply needs of MCAS, New River. One treatment technology that would meet water quality goals is ion exchange softening.

Well water would be pumped to an equalization/aeration tank for this alternative. From the equalization tank, the water is pumped through greensand pressure filters and ion exchange softening units directly into the existing ground storage reservoirs. Pressure filters with greensand media are used to remove iron, manganese and particulate material. This is to prevent fouling of the ion exchange resins and extend the regeneration periods. The filters are automated and provide 3.5 mgd capacity with one filter out of service.

Ion exchange softening does not reduce disinfection by-product precursor material. Corrosion control and disinfection are similar to the ion exchange upgrade alternative discussed above.

The new ion exchange facility alternative would provide similar water quality with similar staffing, O&M costs, and spatial requirements as the ion exchange upgrade alternative. Due to the inherent reliability issues associated with even and extensive upgrade, reliability is somewhat greater than the exchange upgrade alternative. Capital cost of this alternative is $6,000,000, O&M costs are $109,000, and the present value of the alternative is $7,500,000.

2.5. New lime softening facility

Construction of a new conventional upflow clarifier softening facility provides an alternative lime softening technology for consideration. The process is similar to the spiractor upgrade alternative, except that softening is accomplished in conventional upflow clarifiers and all of the equipment and infrastructure are new.

One difference between the spiractor process and upflow clarifier is that the residual waste stream from the upflow clarifier process is a 2-percent to 4-percent sludge (calcium carbonate/water slurry), as opposed to the relatively dry, sand-like material produced by the spiractor operation. Based on the current raw water quality and level of treatment, the sludge stream from a solids contact softening process would consist of approximately 4,000 lbs of dry solids per million gallons of water treated. This would represent approximately 10,000 to 20,000 gallons of waste sludge per million gallons of water treated. The options available for handling and disposal of this waste stream include construction of lagoons for storage, mechanical dewatering, land application of wet or dried sludge, landfill disposal of dried sludge, or discharge of wet sludge stream to sewer system.

Implementation of this alternative would
provide water quality consistent with water quality goals and regulatory requirements. Reliability would be greater than the existing system or the spiractor upgrade alternative; however, due to the inherent reliability issues associated with lime feed systems, this alternative would be less reliable than either ion exchange or membrane alternatives.
Operational and maintenance costs, staffing, and spatial requirements are similar to the existing plant. The approximate capital cost and O&M costs of this alternative are $7,200,000 and $80,000, respectively, and the present value of this alternative is $8,300,000.

2.6. New membrane softening facility

Analysis of the raw water quality from MCAS, New River indicates that either reverse osmosis (RO) or nanofiltration (NF) can be used to soften the water and satisfy the treatment objective. Based upon an analysis of the feedwater quality, the presence of silica and raw water turbidity may be limiting factors that would effect the feasibility of the membrane treatment process. Silica was found in the groundwater at a concentration of 43 mg/l as SiO₂. Based on preliminary modeling, this level of silica will limit RO and NF system recoveries to 65 and 80 percent, respectively. It is likely that the presence of silica was increased because of turbidity in the raw water supply and lower levels may be present. This would allow higher system recovery and reduce capital and operational costs. A more comprehensive water analysis to determine the exact concentration of dissolved silica may allow more reliable cost estimates for the membrane separation option.

Reverse osmosis was selected as the most cost effective option because of the ability to by-pass a portion of the feed water flow around the treatment process. This is because of the high mineral removals obtained by the RO system. By-passing the feed water allows the naturally occurring minerals to be blended with the RO permeate and provide a stable, high quality finished water. In this application, the by-pass water pressure is pumped through greensand filters to remove iron and manganese from the by-pass water prior to blending with the RO permeate.

Membrane systems installed on groundwater supplies use feed pressure from the wells to flow through the pretreatment system. Fig. 2 presents a typical process flow sequence for an RO or NF membrane system. Acid and scale inhibitor are commonly added to the raw water as it enters the treatment facility to minimize the risk of precipitating inorganic compounds in the membranes. Cartridge filters are used to remove particles greater than 10 microns in size that may foul the feed water channels of the membrane module. Cartridge filters operate using pressure differential, normally the clean pressure drop is 3 to 5 psi, and the dirty pressure drop is 15 to 30 psi. The cartridge filter is typically located prior to the booster pump; however, it is proposed after the booster pump for this application because of the low influent pressure from the wells. This will require a more expensive, higher pressure rated cartridge filter module.

Pressure booster pumps are used to increase the feed water pressure needed to operate the membrane system. Typical discharge pressures for RO systems range from 100 to 200 psi. A single pass RO system consisting of two 1.25 mgd trains consisting of 34 pressure vessels containing 7 membrane elements each operating at 65 percent recovery was selected for this evaluation.

After treatment, the permeate may have excessive carbon dioxide levels present from concentrating carbon dioxide found in the well water or generated through the addition of an acid. The carbon dioxide lowers the pH. Degassing to remove the excess carbon dioxide is done to increase the pH and reduce the amount of caustic that must be added after blending of the by-pass water to provide the desired finished water pH. Chlorine and a corrosion inhibitor are then added for disinfection and corrosion control, respectively.

Chemical cleaning of the membrane system is periodically needed to remove materials that accumulate on or foul the membrane. The chemical solution is circulated through the membrane system for a period of time in order to dissolve the foulants and recover membrane system performance.
A primary advantage of the membrane treatment process is that the finished water is a very consistent quality. Operator involvement is generally not required to adjust chemical dosages in order to modify the product water quality to satisfy regulatory requirements. The use of a by-pass feed configuration allows control of the finished water quality. This is done by adjusting the by-pass flow to provide a desired final blended water quality. As higher TDS wells are placed on line, the by-pass flow would decrease to maintain a consistent finished water quality.

Membrane systems are highly automated and typically have minimal operator requirements. Monitoring of process information such as flow, pressure, and water quality parameters is generally automated. Instrument calibration for pH and conductivity meters, collecting water samples and routine equipment maintenance are typical operator activities. Automation and integration of the membrane system to a SCADA system relatively is simple. Operational data from the membrane system can be logged automatically by computer methods. Raw data is "normalized" in order to provide information on the performance of the membrane system under various operating conditions and is used to determine when chemical cleaning is required.

Membrane treatment systems require very modest amounts of land and can be easily located. Most buildings are constructed to allow future expansion of the treatment facility, although this is not an absolute requirement. For this application, a 2,000 square foot building would be required to house the membrane system equipment and associated control room, laboratory and office space. An additional 1,000 square foot building for process chemical storage and feed equipment was also included in the estimate. The buildings, parking and other spatial requirements for the membrane system options could be located on less than an acre of land.

All membrane processes produce a concentrate stream that contains the removed minerals from the feed water. Because of the low recovery rate proposed for the application, the concentrate would contain approximately 1,000 mg/l of TDS. Minerals in the concentrate would be the same as present in the feed water, only concentrated up to 2.9 times the original concentration. Disposal options for the concentrate include discharge to the sewer collection system or a brackish water discharge. Permitting and costs associated with disposal of the concentrate were not included in the evaluation because of the limited information.

Capital equipment costs were estimated based on the equipment described in Section 5.5.3. Construction costs do not include rehabilitation of the supply wells nor concentrate disposal options that are evaluated on a case by case basis. Using the above considerations, construction costs for a 3.5 mgd membrane softening system is estimated at approximately $5,300,000.

Operational and maintenance costs for a membrane system can typically be divided into five major categories including labor, chemicals, power, membrane replacement, and other costs such as cartridge filters, chemical cleaning, etc.

Operating costs are estimated to be $112,000 per year at an average production flow of 1.0 mgd or $0.30 per 1,000 gallons of treated water. Finished water and well water pumping included in current operating costs are not included. Overall present value of this alternative is estimated to be $6,700,000.

2.7. Purchase water from Onslow County

This alternative considers purchasing potable water from the Onslow County Water Department. Onslow County currently provides potable water service to the areas surrounding the MCAS, New River facility. The primary drinking water supply for the County consists of a series of wells that withdraw from the Cretaceous aquifer. In
1996, two water supply and treatment systems were developed in the Snead’s Ferry and Hubert areas in the County. These new water systems withdraw water from the Castle Hayne aquifer and provide greensand treatment for iron and manganese removal followed by ion exchange softening.

Water quality in the Onslow County water system currently meets all drinking water standards and can be characterized as a moderately hard, low in natural organic compounds (NOM) that can form disinfection by-products, and non-corrosive. The distribution system appears to be well maintained with regular flushing and microbial monitoring.

Water source and treatment capacity would require expansion should MCAS, New River elect to purchase potable water from Onslow County. The ability to expand the current source and treatment capacities have been incorporated into the current Onslow County water system and could be accomplished with minimal effort. Installation of new wells, water line to the existing treatment facility, and expansion of the existing water treatment plant would be needed.

The capital cost for this alternative includes the cost of the additional pipelines and upgrades to Onslow County treatment system. Without detailed cost estimates and negotiated percentages that the Navy would be responsible for, exact costs can not be determined. Capital costs for required improvements are estimated at $5,000,000. Maintenance costs include the current water rate of $2.55 per 1000 gallons. Based on average water use of 1.0 mgd, the annual water purchase cost would be approximately $930,000. This is based on current rates that are subject to increase as system operating costs increase in the County. Operation and maintenance costs for distribution, storage, re-pumping and chlorine booster stations are not included.

Purchasing potable water from Onslow County would release MCAS, New River from the responsibilities of owning and operating a water treatment plant. However, purchasing water from Onslow County introduces new operating procedures associated with operating a consecutive system. Operating a consecutive system requires an understanding of water quality management. Purchasing water from Onslow County also leaves the base little control over the quality of water supplied for base operations. Although the reliability of the water quality supplied by Onslow County has been found to be in good standing, the base is dependent on Onslow County to deliver adequate quantities of water making this alternative unattractive to the base. Although it is feasible for the base to purchase water from Onslow County it may be in the best interest of the base to continue to be independent of a water supplier.

Although capital cost for the required treatment and distribution system improvements are $5,000,000, the life cycle cost over a 20-year period indicates that purchasing water from the county is the least cost effective alternative just over $16,500,000 due to current County water rates.

3. Evaluation

Evaluation of these alternatives is based on five specific criteria, listed below in order of importance:
- Reliability
- Capital cost
- O&M cost
- Staffing requirements
- Spatial requirements.

With the exception of the no action alternative, all of the alternatives will meet the water quality goals with reasonable reliability. The no action alternative is not viable and is not included in the evaluation. The other alternatives were evaluated and ranked based on the criteria presented above.

3.1. Alternative ranking

Order-of-magnitude capital costs were
Table 1
Raw and normalized capital and O&M costs

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Capital cost ($)</th>
<th>Capital cost rating</th>
<th>O&amp;M cost (annual $)</th>
<th>O&amp;M rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiractor-upgrade</td>
<td>4,617,000</td>
<td>1.39</td>
<td>70,000</td>
<td>0.49</td>
</tr>
<tr>
<td>Exchange-upgrade</td>
<td>4,955,000</td>
<td>1.49</td>
<td>109,000</td>
<td>0.77</td>
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<tr>
<td>Ion exchange-new</td>
<td>6,061,000</td>
<td>1.83</td>
<td>109,000</td>
<td>0.77</td>
</tr>
<tr>
<td>Lime softening-new</td>
<td>7,274,000</td>
<td>2.19</td>
<td>80,000</td>
<td>0.57</td>
</tr>
<tr>
<td>Membrane softening</td>
<td>5,264,000</td>
<td>1.59</td>
<td>112,000</td>
<td>0.79</td>
</tr>
<tr>
<td>Onslow County</td>
<td>5,000,000</td>
<td>1.50</td>
<td>931,000</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Table 2
Ranking based on raw criteria score

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Total raw score</th>
<th>Reliability</th>
<th>Capital cost</th>
<th>O&amp;M cost</th>
<th>Staffing</th>
<th>Spatial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiractor-upgrade</td>
<td>10.4</td>
<td>3.125</td>
<td>1.4</td>
<td>0.5</td>
<td>2.777</td>
<td>2.564</td>
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<tr>
<td>Ion exchange-upgrade</td>
<td>7.82</td>
<td>1.563</td>
<td>1.5</td>
<td>0.8</td>
<td>1.388</td>
<td>2.564</td>
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<tr>
<td>Ion exchange-new</td>
<td>5.95</td>
<td>0.938</td>
<td>1.8</td>
<td>0.8</td>
<td>1.388</td>
<td>1.026</td>
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<tr>
<td>Lime softening-new</td>
<td>10.33</td>
<td>2.188</td>
<td>2.2</td>
<td>0.6</td>
<td>2.777</td>
<td>2.564</td>
</tr>
<tr>
<td>Membrane softening</td>
<td>5.13</td>
<td>0.313</td>
<td>1.6</td>
<td>0.8</td>
<td>1.388</td>
<td>1.026</td>
</tr>
<tr>
<td>Onslow County</td>
<td>10.51</td>
<td>1.875</td>
<td>1.5</td>
<td>6.6</td>
<td>0.277</td>
<td>0.256</td>
</tr>
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</table>

Table 3
Ranking based on weighted criteria score

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Total weighted score</th>
<th>(0.4) Reliability</th>
<th>(0.25) Capital cost</th>
<th>(0.15) O&amp;M cost</th>
<th>(0.1) Staffing</th>
<th>(0.1) Spatial</th>
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</thead>
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<tr>
<td>Membrane softening</td>
<td>0.88</td>
<td>0.125</td>
<td>0.4</td>
<td>0.1</td>
<td>0.139</td>
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<tr>
<td>Ion exchange-new</td>
<td>1.18</td>
<td>0.375</td>
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<td>0.1</td>
<td>0.139</td>
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<tr>
<td>Onslow County</td>
<td>2.17</td>
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<td>0.99</td>
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<td>0.025</td>
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<tr>
<td>Ion exchange-upgrade</td>
<td>1.51</td>
<td>0.625</td>
<td>0.4</td>
<td>0.1</td>
<td>0.139</td>
<td>0.256</td>
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<tr>
<td>Lime softening-new</td>
<td>2.05</td>
<td>0.875</td>
<td>0.55</td>
<td>0.09</td>
<td>0.278</td>
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<td>1.25</td>
<td>0.35</td>
<td>0.075</td>
<td>0.278</td>
<td>0.256</td>
</tr>
</tbody>
</table>

established based on the equipment and construction requirements of each alternative. To allow alternative costs to be evaluated concurrently with intangible criteria, such as reliability and staffing, a system was developed for rating the costs on a scale of 0 to 10. Summing the costs of all of the alternatives and dividing the sum into the capital cost estimate for the individual alternatives normalized the capital cost for each alternative. These normalized costs can vary from zero to one with the normalized costs being directly proportional to actual cost. For example, if the cost of an alternative was twice that of another, its normalized cost would also be twice that of
the other. The normalized rank for each alternative was then multiplied by ten to obtain ratings on a 0 to 10 scale. The O&M costs were normalized and rated in a similar manner.

Table 1 shows the capital and O&M costs and ratings for each alternative. From a capital cost basis, the least expensive alternatives are the two upgrade alternatives. Of the new construction alternatives, the membrane treatment alternative is the least expensive, with a capital cost similar to the upgrade alternatives and significantly lower than the other new treatment facility alternatives.

From an O&M cost basis, the lime softening alternatives are least expensive, followed by the ion exchange alternatives, membrane treatment, and the Onslow County alternative. Due to the cost of the purchased water, the O&M cost of the Onslow County alternative is an order of magnitude greater than the other alternatives.

All other evaluation criteria were rated on a scale of 1 to 10, with one representing best performance. Reliability was evaluated based on ability to deliver water at required flow and pressure as well as quality consistent with regulatory compliance. For reliability, staffing, and spatial requirements, the lowest ranked alternative was assigned a value of ten and the best a value of one. Table 2 shows ratings and overall ranking for each alternative. Based on these raw scores, the membrane treatment and ion exchange alternatives are approximately equivalent, followed by the precipitative softening alternatives and the Onslow County alternative.

Because all evaluation criteria are not of equal importance, weighting factors were assigned to criteria as follows:

- Reliability: 0.40
- Capital cost: 0.25
- O&M cost: 0.15
- Staffing: 0.10
- Spatial: 0.10

As indicated by the weighting factors, it was assumed that reliability is the most important aspect of a treatment strategy, followed by capital cost, O&M cost, staffing requirements, and spatial requirements. Table 3 presents the ratings assigned and ranks each of the alternatives. Based on this weighting of the criteria, the membrane softening alternative is the best option, followed by construction of a new ion exchange facility.

4. Conclusions

Seven alternatives were evaluated to determine the most effective water supply strategy for MCAS, New River to ensure adequate flow, pressure, and quality of potable water. It was determined that the no action alternative was not acceptable due to plant deficiencies that have caused regulatory compliance violations. In addition, future regulations, particularly those associated with disinfection by-products, indicate that a change in treatment strategy should be made. Of the remaining six alternatives, the membrane softening alternative is the best strategy based on raw and weighted sums of the numerically assessed evaluation criteria.