MAKING THE RIGHT DECISION: HOW ONE COUNTY IS MEETING CCPCUA REGULATIONS WITH MEMBRANE TREATMENT

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ABSTRACT

In the Central Coastal Plain of North Carolina, groundwater from the Cretaceous aquifer system is being withdrawn at a rate that exceeds the available recharge. In 2002, the Central Coastal Plain Capacity Use Area (CCPCUA) regulations were established to reduce existing groundwater withdrawals from the Cretaceous aquifer system. The regulations call for a 25 percent reduction every five years over a 15-year period, equivalent to an overall withdrawal cutback of 75 percent. This applies to wells located in the dewatering and saltwater encroachment zones of the Central Coastal Plain.

Before the CCPCUA rules were established, Craven County's water supply system relied heavily on groundwater wells that drew from the cretaceous Black Creek Aquifer and Pee Dee Aquifer. Craven County was initially permitted to withdraw an average of 2.69 MGD from these aquifers. However, under the CCPCUA rules, the County's 2018 total permitted raw water supply capacity would be reduced to 1.39 MGD. Population projections and corresponding water demand projections indicated an average day demand of 2.62 MGD in 2018. If the County took no action, it would experience a raw water supply shortfall of approximately 1.23 MGD.

McKim & Creed and Craven County teamed to evaluate the County's raw water deficit and to develop several options for comprehensive new potable water infrastructure. Craven County decided to pursue a new raw water supply from the Castle Hayne Aquifer and to utilize membrane treatment. Engineers conducted a pilot membrane system and used the results to predict the expected permeate water quality, fine-tune the system, complete toxicity testing and mixing models for the concentrate, and perform membrane autopsies to analyze scale and fouling. This data is now being used in the design of the new potable water supply and treatment facilities.

In this presentation, we will discuss the process that led to Craven County's decision to pursue the new raw water supply and membrane treatment. We will address the specific water-quality issues that Craven County faced, including the presence of organic carbon and high iron, as well as hardness (calcium and silica) and alkalinity concentrations. We will review the results from the pilot plant operation and discuss how the obstacles typically associated with membrane treatment will be overcome in the design for the new Craven County Potable Water Supply and Treatment Facilities.

KEYWORDS

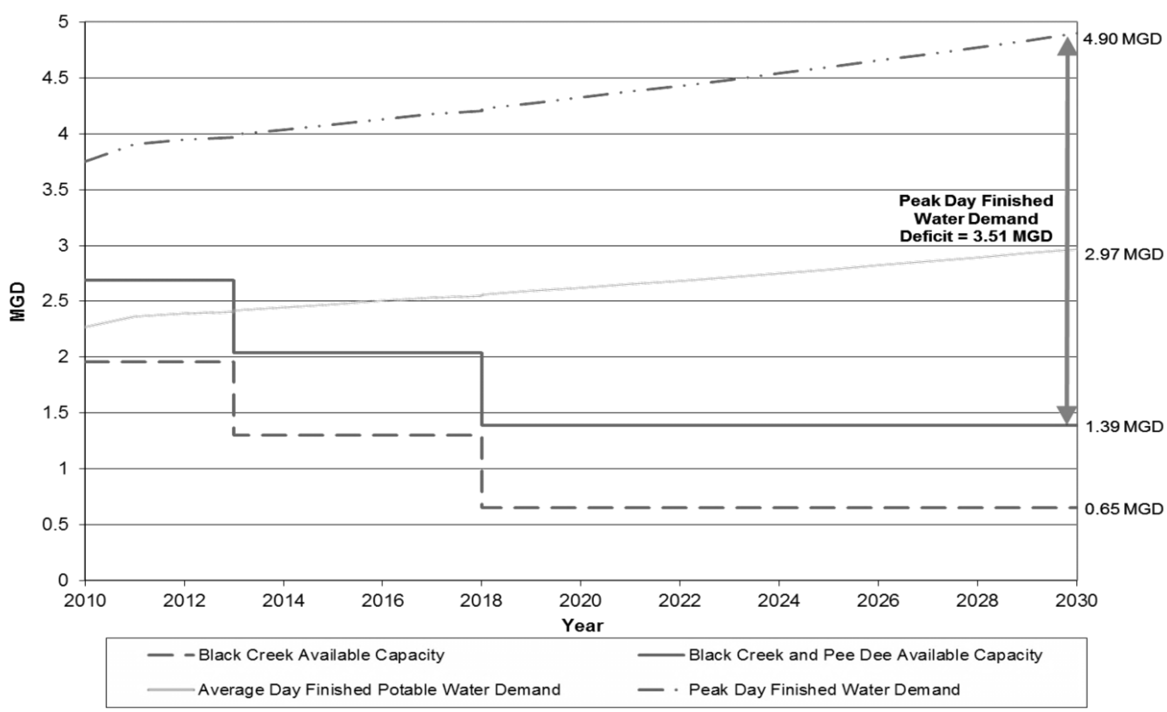
Central Coastal Plain Capacity Use Area (CCPCUA), Groundwater, Potable Water Treatment, Membrane Treatment, Pilot Study, Toxicity Testing, Water Quality

INTRODUCTION

In the Central Coastal Plain of North Carolina, groundwater from the Cretaceous aquifer system is being withdrawn at a rate that exceeds the available recharge. In December 1998, the North Carolina Division of Water Resources (DWR) requested that the Environmental Management Commission (EMC) consider designating a capacity use area to address threatened groundwater supplies in this region. In 2002, the Central Coastal Plain Capacity Use Area (CCPCUA) regulations were established to reduce existing groundwater withdrawals from the Cretaceous aquifer system in the Central Coastal Plain. The regulations call for a 25% reduction every five years over a 15-year period, equivalent to an overall withdrawal cutback of 75%. This applies to wells located in the dewatering and saltwater encroachment zones of the Central Coastal Plain.

Craven County is one of the many utilities in the Central Coastal Plain that is facing a growing deficit in water supply. Before the CCPCUA rules were established, Craven County's water supply system relied heavily on groundwater wells that drew from the cretaceous Black Creek Aquifer and Pee Dee Aquifer. Craven County was initially permitted to withdraw an average of 2.69 MGD from these aquifers, but since the Pee Dee aquifer is not currently affected by the CCPCUA reductions, the required reductions will only affect Craven County's permitted withdrawal capacity from the Black Creek Aquifer. The first CCPCUA reduction (25% or 0.65 MGD) was required by August 2008 and reduced the County's permitted withdrawal from the Black Creek Aquifer to 1.96 MGD. Two additional 25% (0.65 MGD) reductions are required by August 2013 and August 2018 respectively. After August 2018, the County's permitted withdrawal from the Black Creek Aquifer is expected to be only 0.65 MGD, unless DWR sees evidence that the last reduction is not necessary based on observed aquifer recovery. This means that, including the permitted capacity from the Pee Dee Aquifer (0.73 MGD), the County's 2018 total permitted raw water supply capacity would be only 1.39 MGD.

Figure 1 - Comparison of Projected Average and Peak Day Water Demand vs. Existing Raw Water Supply



Population projections and corresponding water demand projections for Craven County were completed through a planning horizon of 2030 and indicated an average day demand of 2.62 MGD in 2018 and a peak day demand of 4.32 MGD. Peak day demands can be accommodated by the cretaceous aquifers because DWR permits limit total annual withdrawals rather than limiting daily withdrawals. Thus, it is possible, on a short-term basis, for Craven County to pump more than the calculated daily permitted withdrawal from its cretaceous supply and make up the difference by pumping less than the calculated daily allowable volume in a low-demand month. As indicated in Figure 1, if the County took no action to increase its raw water supply beyond the current Black Creek and Pee Dee wells, it would experience a shortfall of approximately 1.23 MGD in 2018.

Regional water demand projections through the year 2020 in the Central Coastal Plain indicate a growing deficit in water supply. In a CCPCUA fact sheet, DWR indicates that other sources of water, including surface water and other aquifers such as the high-yield Castle Hayne aquifer, must be developed to address this growing deficit in water supply. As discussed above, projections show that the County will be unable to supply sufficient finished potable water to its customers after the second CCPCUA mandatory reduction in 2013. As such, it will need to replace the lost capacity with an alternative water supply such as the Castle Hayne aquifer.

METHODOLOGY

Preliminary investigations

McKim & Creed teamed with Craven County and evaluated several options for comprehensive new potable water infrastructure in the Preliminary Engineering Report. The conclusions and recommendations of that report strongly favored the alternative of developing the Lower Castle Hayne Aquifer for a sustainable water supply in the future for Craven County. In addition, the application of membrane technology was the most cost-effective alternative for treatment of the raw water. The membrane treatment alternative provides potable water quality that would be the most compatible with the existing Black Creek water quality. With the exceptions of relatively high total alkalinity (460 mg/l as $CaCO_3$ average) and sodium (157 mg/l average), the water quality from the Black Creek Aquifer is exceptional and requires only free residual chlorination for disinfection.

The raw water quality from a series of test wells in the Lower Castle Hayne Aquifer at the proposed production well locations is summarized in Table 1. Generally, the water quality is high in total alkalinity, total hardness, total organic carbon (TOC), and ferrous iron. Only trace amounts of sulfide were detected from the test wells, and these are not considered significant. High concentrations of alkalinity contribute to taste problems in finished water, and high concentrations of TOC contribute to taste, odor, and disinfection by-product formation with free residual chlorination for disinfection. The ferrous iron concentrations are well above the EPA maximum contaminant level of 0.3 mg/l. With proper pretreatment, membrane technology was determined to be the most effective technology to remove these contaminants and permit the application of free residual chlorination for disinfection to be compatible with the existing Black Creek water supply.

Pilot study

In August 2011, a 25,000-GPD pilot scale reverse osmosis (RO) system supplied by Harn RO was installed at the proposed water treatment plant site treating water from test well "WTP." The purpose was to evaluate the feasibility of the application of RO membrane technology for direct treatment of the raw water without the addition of more traditional pretreatment methods for iron and TOC removal. The design of the pilot plant was a scaled down version of the proposed full-scale RO plant to provide some predictability or validation of the performance of the full scale RO system. The main hydraulic design parameters of the pilot system are identical to the proposed full scale production design, including array ratio, vessel length, membrane flux rates and system recovery.

Table 1- Lower Castle Hayne Test Well Water Quality

PARAMETER	WTP (mg/l)	LF1 (mg/l)	FB3 (mg/l)	SP3 (mg/l)	FB4 (mg/l)	FB5 (mg/l)	Average (mg/l)
Total Alkalinity ($CaCO^3$)	212	252	234	233	222	222	229
Total Hardness ($CaCO^3$)	208	241	225	216	233	209	222
TDS	255	316	311	296	302	251	289
Iron	3.27	2.22	1.21	1.59	1.28	1.49	1.84
Sodium	6.48	6.53	6.88	6.36	6.49	6.62	6.56
Chloride	8.5	9.0	--	7	--	5	7.4
pH	7.2	8.29	8.27	7.38	7.31	7.62	7.68
Silica	25	--	--	--	--	--	25
TOC	7.42	--	--	--	--	--	7.42

The self-contained pilot system included a well water booster pump, scale inhibitor feed system, 5 micron nominal cartridge prefiltration system for removal of particulates and control of silt density index (SDI), high pressure feed pump, interstage booster pump, control system for adjusting production rate and recovery, pressure vessel assemblies with membranes designed for operation at 70% to 85% recovery, instrumentation and controls for operation of the system and monitoring system performance, and sample points for collection of samples for chemical analysis. The pilot plant with clean-in-place (CIP) system was completely pre-plumbed, pre-wired, and shipped in a 43-foot shipping container for easy installation and start-up.

The basic design of the pilot system consisted of a 2:1 array, with each of the three membrane arrays consisting of seven membranes in series to simulate the full-scale system and incorporating an interstage booster pump. The main hydraulic design parameters selected were an average system membrane flux of 13.2 gallons per square foot per day (gfd), an average first stage flux of 13.4 gfd, an average second stage flux of 12.8 gfd and an initial recovery rate of 75%. The flux balance was achieved with the interstage booster pump. Control of the RO feed pump and the interstage booster pump is by speed control through variable frequency drives (VFDs) to maintain design flow and membrane flux rates through proportional-integral-derivatives (PID) control loops. Control can also be achieved by manual control of the pump speed. A third PID control loop also controls the concentrate flow by modulating a flow control valve on the concentrate line.

On-line instrumentation was provided to continuously monitor conductivity, temperature, pH, operating flows and pressure. Data on the operation of the pilot system was collected and logged daily. System profiles include data on virtually every aspect of the system operation, including permeate flow and conductivity from each membrane pressure vessel and performance of each stage of the RO system. Data collected and/or calculated and recorded on a daily basis included the following: cartridge filter influent and effluent pressure, RO feed pump hour reading, feed pH, feed temperature, feed and total permeate conductivity, percent salt rejection, RO feed pressure, 1st stage concentrate pressure, 2nd stage feed pressure, total concentrate pressure, 1st stage and total permeate flow and pressure, total concentrate flow, and percent recovery. Data was entered into a spreadsheet and normalized to compensate for the variations in temperature, feed water salinity, permeate pressure, permeate salinity and membrane age. Normalization allows for a more accurate evaluation of the performance of the membrane system.

The pilot system utilized 4-inch diameter by 40-inch long Hydranautics ESPA-4 low-pressure RO membrane elements. Due to the high concentration of sodium and ferrous iron in the raw water, low-pressure RO membranes were selected for the pilot plant. These membranes have a higher salt rejection capability than nanofiltration membranes. The elements are encased in fiberglass pressure vessels, allowing the membranes to operate at higher pressures and to provide a means for separating the feed, concentrate, and permeate streams.

RESULTS / DISCUSSION

It has been shown that RO systems effectively reject dissolved iron in a reduced form, ferrous iron, up to the solubility limit of the ion. However, if the ferrous iron is oxidized by dissolved oxygen or other oxidizing agents to ferric iron, it will precipitate out of solution and foul RO membrane systems. SDI testing during the operation of the pilot plant indicated very low levels of suspended solids, which provided assurance that the iron remained in a reduced or dissolved form in the feed water. SDI test results were generally less than 2.5 during the operation of the pilot system. Membrane manufacturers generally require feed water SDI to be less than 5 for warranty purposes.

The pilot system was configured to produce 16.4 gpm of permeate at an initial recovery of 75%, which yields an average permeate flux of 13.2 gfd. The pilot operated at this configuration for the first month. During this time, the 2nd stage normalized permeate flow was gradually declining indicating some scaling in the 2nd stage. In order to achieve a more stable and sustainable operation, the recovery was reduced to 70% for the duration of the pilot test resulting in stable operation.

A pretreatment acid feed system was provided with the pilot system, but it was not used during the pilot testing. It was calculated that the Langelier Saturation Index (LSI) of the concentrate water was about +1.75 at 75% recovery and +1.6 at 70% recovery. This is in the range where a good scale inhibitor will minimize the precipitation potential of calcium carbonate. Because scale inhibitors effectively inhibit calcium carbonate scaling in addition to iron scaling, it is unlikely that acid feed will be required. However, providing an acid feed system with the full-scale RO system provides the ability to reduce the feed water pH if necessary to control particulate iron formation.

Differential pressure monitoring at the nominal 5-micron prefiltration system indicated that replacement of the prefilter cartridges will be necessary on a roughly monthly basis. It is also recommended to utilize filters with a 98% efficiency rating to minimize passage of particulates to the RO system to minimize fouling potential.

Evaluation of the normalized permeate flow decline and the normalized feed/concentrate differential pressure increase in the 1st and 2nd stages indicated that chemical cleaning may be required approximately two to four times per year. The actual cleaning frequency will be determined by monitoring the operation and performance of the full-scale RO system. A membrane element autopsy was performed on the second stage tail element used in the pilot system after scaling was suspected to be occurring. The autopsy determined that iron oxide was the primary constituent on the membrane surface. A flat sheet sample of the membrane was successfully cleaned using Avista RoClean L403 low pH cleaner followed by L211 high pH cleaner.

A typical analysis of the feed, permeate, and concentrate water streams from the pilot study is summarized in Table 2.

Table 2 – Analytical Data from Pilot Study (Oct. 20, 2011)

PARAMETER	FEEDWATER (mg/l, ion)	PERMEATE (mg/l, ion)	CONCENTRATE (mg/l, ion)
Calcium	78.7	0.8	239
Magnesium	1.5	<0.1	4.5
Sodium	5.7	1.2	15.4
Potassium	2	0.3	5.5
Bicarbonate Alkalinity	251.3	10	612
Sulfate	<5	ND	<5
Iron	2.9	0.1	8.8
Silica	25	ND	61.6
TDS	252	10	751
pH	7.4	6.0	7.6
TOC	7	<1	27.6

Environmental considerations

McKim & Creed investigated a number of alternatives for disposal of the concentrate water from the membrane treatment system in the Engineering Alternatives Analysis (EAA). These included disposal and treatment at a wastewater treatment plant, land application, evaporation, and disposal via a submerged diffuser in the Neuse River Estuary (NRE). The recommendation from the EAA was to pursue an NPDES permit for disposal in the NRE.

Based on this recommendation, McKim & Creed retained Tetra Tech (TT) to develop an Environmental Fluid Dynamics Code (EFDC) model and Water Quality Analysis Simulation Program (WASP) to evaluate the environmental impact of the proposed discharge on the NRE during a critical period of time when the expected discharge would have an adverse impact on the ambient water quality. A low-velocity period was targeted (January 1, 1998 through December 31, 2006) to minimize the momentum mixing, due to differences in the velocity of the effluent and the ambient water velocity. Selecting this period balanced the objectives of finding a period of low salinities and low velocity which would provide the least dilution for the effluent plume.

A fine nested grid in the NRE was developed and calibrated in combination with an embedded EFDC jet-plume subroutine to evaluate the performance of the proposed multiport diffuser in the NRE. Since the proposed discharge does not contain constituents that would cause impacts on dissolved oxygen levels in the river, the study focused on chronic dilution levels and not algal or oxygen responses. The water quality testing results obtained from samples of the concentrate water from the pilot test were used in the model for the discharge to the NRE. EFDC simulation salinity values for the NRE were obtained during the calibration and validation of the model developed by TT.

The diffuser design consists of twelve 3-inch diameter Tideflex diffuser valves spaced at 5 feet apart, oriented seaward and angled up at 30 degrees from the horizontal plane. The diffuser is about 70 feet in length and is constructed of 18-inch HDPE DR11 pipe, secured at the bottom of the river approximately 1,000 feet from shore at a depth of about 10 feet. The distance of the discharge ports above the bottom of the river bed is about 26 inches. The exit velocity at the nozzles at design flow is about 7.8 feet per second.

The modeling analysis was conducted to assess the chronic dilution of the discharge based on a four-day moving average dilution. In North Carolina, the chronic mixing zone should not exceed one-third of the width of the receiving stream; however, the NRE is approximately four miles wide at the location of the diffuser. VPlumes output included the three-dimensional path of the effluent plume and the dilution at each output location. The 10^{th}, 50^{th}, and 90^{th} percentiles of the chronic dilution were determined at nominal distances along the plume path.

The statistics describing the chronic dilution plume during the selected period showed little variability. The plume was diluted by an order of magnitude within one meter of the diffuser and increased another order of magnitude 10 meters from the diffuser. The membrane system concentrates the groundwater by a factor of about 3.3, and the submerged diffuser design achieved that level of dilution within one meter of the diffuser.

Samples of the concentrate water from the membrane system were collected and sent to Environmental Testing Solutions, Inc. for whole effluent toxicity testing. The study was designed to evaluate the toxicity of the effluent on a salt water species of Mysid shrimp to determine potential impacts to the estuarine receiving water. Results of the study show significantly reduced Mysid growth in the full strength effluent. The resulting noobserved effect concentration (NOEC) was 50% strength. The seven-day IC_{25} (25% inhibition concentration) was greater than 100%. Mysid survival and fecundity were not reduced in the concentrate samples from the RO pilot system.

A characterization of the benthic habitats in the vicinity of the proposed diffuser location was completed by Land Management Group, who also completed the wetland and threatened and endangered (T&E) species evaluations for the project. The benthic habitats in the vicinity of the project area include shallow, sandy subtidal estuarine areas near shore, and deep muddy estuarine habitat in the middle of the river. These habitats contain fine-grained organic sediment with benthic community consisting of aquatic insects and their larvae. This portion of the river contains high sediment contamination and sediment toxicity. Total faunal abundance is relatively low but not considered to be degraded. Dominant species in this area include insect larvae (Chironomidea), polychaetes (Spionidae), bivalves (Dreissenidea), oligochaetes (Tubificidae), and polychaetes (Capitellidae). Taxa richness and diversity near the project site were relatively low. Benthic invertebrate communities appear to consist of common taxa that are abundant in most estuarine waters in North Carolina. Generally, the salinity and subsequently the density of the discharge are lower than that of the river, which will cause the discharge to rise towards the water surface in the river. Therefore, the discharge is anticipated to have virtually no impact on the benthic communities in the vicinity of the discharge.

Basis for design

The proposed membrane treatment facility will be designed to meet the expected maximum day demand until the year 2030. Therefore, the treatment facility should be designed with an ultimate capacity of 4.0 MGD. Typically, a 4.0 MGD membrane WTP would be designed with four 1.0 MGD membrane skids. However, the proposed plant design will provide a redundant membrane skid to compensate for any existing wells or membrane skids failing or to provide enough capacity to continue to meet demands during CIP cycles or other maintenance activities where a membrane skid must be taken out of service. Craven County's new membrane water treatment plant will have an initial design capacity of 2.0 MGD with an add alternate design to achieve 3.0 MGD and be easily expandable to 5.0 MGD by adding additional membrane skids.

Based on an initial capacity of 2 MGD, five (5) approximately 200-300 feet deep 12" gravel pack raw water wells were recommended. The wells will be placed approximately 2,000 feet apart and adjacent wells will be operated on alternating pumping cycles to minimize aquifer drawdown and maximize recovery.

Based on process projections and the pilot plant operation results, it is prudent to include both sulfuric acid and scale inhibitor chemical addition systems before the membrane skids. The sulfuric acid system lowers the feedwater pH to inhibit calcium carbonate scaling and biofouling of the downstream membranes and also ensures that the naturally occurring iron present in the feedwater is kept in its reduced, soluble form (to prevent mineral fouling of the membranes). Scale inhibitor is crucial to maintaining membrane integrity, and minimizes the risk of mineral scale and subsequent short operation cycles between membrane cleaning cycles. Scale inhibitor chemicals are used to prevent calcium carbonate and sparingly soluble salts from scaling on the membrane system as they become more concentrated, to the point of exceeding their solubility limit. The addition of scale inhibitor, further ensures that the iron in the water is kept in its ferrous (soluble) form and will be rejected by the membranes. The operation of the pilot test confirmed that the use of a non-phosphonate based scale inhibitor such as Avista's Vitec 1000 is appropriate to prevent by-product water with unacceptable amounts of phosphorus.

In order to protect the membrane skids and feed pumps, a physical barrier protection system is needed to keep particulate matter from the membrane equipment. Cartridge filters will be installed at the water treatment facility upstream of the membrane skids. The filters will be installed in parallel, and will be designed such that all filters are in service, no matter how many membrane skids are in operation.

Post treatment

With the high concentrations of iron and TOC in the groundwater, blending of the raw water with the membrane permeate water to provide sufficient calcium and alkalinity to stabilize the finished water quality is not feasible. A 5% raw water blend with the permeate water will exceed the EPA maximum contaminant limit of 0.3 mg/l iron in the finished water. In addition, the high TOC in the groundwater will result in sufficient concentrations of organics in the finished water to increase disinfection byproduct formation in the finished water with free residual chlorination for disinfection.

A number of alternatives were investigated to stabilize the finished water quality, including an alternative water supply from another aquifer, side stream treatment of the well water for iron and TOC removal, lime feeder system, magnesium hydroxide feed system, and calcite filtration. After an extensive alternatives analysis, the construction of a post-treatment calcite filter system was selected as the most cost-effective approach to finished water stabilization. The upflow filter system is designed to increase the total alkalinity and calcium in the finished water to about 35 to 40 mg/l. Any remaining carbon dioxide concentrations in the water will be converted to carbonate alkalinity by final pH adjustment with sodium hydroxide.

The calcite filer system consists of two upflow filter systems, each having four cells with a surface area of 352 square feet per cell. The design operating loading rate is 4 gpm per square foot, and the design operating media depth ranges from 4.5 to 5.5 feet. The calcite media is consumed during the filtration process, and the rate of consumption varies depending on the quality of the feed water, characteristics of the calcite media, surficial velocity through the media, temperature, and other factors. A pneumatic conveyor system is proposed to periodically refill the calcite filters with bulk calcite media. After refill, a restratification backwash cycle levels the media in the filter bed.

In addition to the calcite filters, post treatment chemical addition will be provided using sodium hydroxide for final pH adjustment, sodium hypochlorite for free residual chlorination for disinfection, and zinc orthophosphate for additional corrosion protection of the finished water distribution piping.

CONCLUSION

To address the CCPCUA regulations in Craven County, McKim & Creed recommended developing a well field in the Lower Castle Hayne Aquifer to provide water to a membrane water treatment plant. Pilot study results verified the appropriateness of using membrane treatment with Craven County's Lower Castle Hayne Aquifer as the water supply source. Further, environmental studies affirmed that the concentrate produced from the proposed membrane system should be acceptable for discharge to the Neuse River. McKim & Creed is currently working on the design of the new comprehensive potable water infrastructure for Craven County to address the water shortages resulting from CCPCUA regulations in combination with a moderately growing population. The project includes a 5.0 MGD membrane treatment facility with calcite filters, raw water supply wells, raw water and finished water transmission mains, concentrate transmission pipeline, and submerged concentrate diffuser.

ACKNOWLEDGEMENTS

Rusty Hayes – Superintendent – Craven County
Jack B. Veit, III – County Manager – Craven County
Richard F. Hemphill – Finance Officer – Craven County
Jonathan R. Harn – Project Engineer – Harn R/O Systems, Inc.
Tetra Tech
Jim Sumner – Laboratory Director - Environmental Testing Solutions, Inc.
James K. Holley – Senior Hydrogeologist – Groundwater Management Associates, Inc.
Richard K. Spruill – Principal Hydrogeologist – Groundwater Management Associates, Inc.
Scott Skipper – Skipper's Well Drilling
Environmental Chemists, Inc.