A Winning Combination

Innovative MBR technologies and reclaimed water dispersal systems overcome challenges to wastewater treatment in North Carolina coastal areas — meeting strict regulations, protecting nearby ecosystems, and appealing to residents

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North Carolina's coastal region, and in particular its associated estuaries, is among the most biologically productive and environmentally sensitive area of the state and the nation. However, North Carolina's coastal counties are experiencing some of the fastest population growth in the Southeastern United States. The resulting, often-conflicting, needs of the expanding human population place undue pressure on these crucial estuarine resources and threaten the very features that make the area so economically desirable.

Recently enacted regulations and statutes have significantly restricted how wastewater is managed from new or expanding communities on the Carolina Coastal Plain. Prior solutions, involving use of homeowner-association-managed factory-built wastewater treatment plants or three-cell facultative lagoons that discharge to tidal creeks and estuaries, have produced a variety of water quality problems leading to ecological degradation of sensitive shellfish waters. In light of these issues, McKim & Creed (Raleigh, N.C.) has recently completed designs for six new satellite reclaimed water facilities ranging in size from 380 to 1900 m^3/d (0.1 to 0.5 mgd) to serve new coastal communities. Each design utilizes a multiple-barrier approach and incorporates chemically enhanced biological nutrient removal (BNR) processes with membrane or cloth disk filtration and UV disinfection to produce extremely high-quality reclaimed water. Due to the coastal location and associated high risk of hurricane exposure, each facility was designed with dual treatment trains, full standby emergency power generation, and 5-day lined upset basins. In addition, due to the upscale nature of these communities, special precautions were implemented to improve aesthetics and minimize the risk of odors.

Waterfront Communities and Effluent Management

Since 2005, McKim & Creed has worked with private developers to find environmentally sound wastewater solutions at six new upscale waterfront communities. Each of the 200- to 300-ha (500- to 800-ac) properties was developed for single family homes and located on waterfront property adjacent to the Atlantic Intracoastal Waterway or interconnecting tidal creeks. The communities consisted of between 200 and 1100 individual lots, 40% of which featured water frontage on coastal estuaries, marinas, manmade lakes, freshwater wetlands, or high-quality shellfish waters.

Lot sizes varied from 0.1 to 0.6 ha (0.3 to 1.5 ac), and most of the developments included site amenities such as yacht or clubhouse facilities, marinas, boat ramps, lakes and water features, community centers, swimming pools, tennis courts, fire rings, hiking and biking trails. The typical cost for individual lots within these developments ranged from $100,000 to $1.2 million.

Due to the remote location of each new community, connecting to an existing municipal collection system was not feasible. Therefore, management strategies for handling treated effluent had to be developed before selecting and designing an appropriate treatment process.

The fact that each site was located in close proximity to sensitive and ecologically diverse coastal marshes made an environmentally acceptable solution more complex.

Effluent management alternatives that were considered included:

- Direct discharge to "waters of the state" via a new National Pollutant Discharge Elimination System permit,
- Disposal of biologically treated effluent via low-rate spray irrigation to land,
- Beneficial reuse of reclaimed water onsite via independent spray or drip irrigation on lawns, planting beds, common areas, or via individual residential irrigation systems, and
- Direct groundwater discharge to surficial aquifers via excavated infiltration basins designed as site amenities.

Environmental concerns in recent years have caused the North Carolina Department of Environment and Natural Resources to pass stringent regulations that effectively preclude new direct discharges from wastewater treatment facilities in coastal counties. This made the option of obtaining a new permit for surface water discharge essentially infeasible.

Land application by spray or drip irrigation was technically feasible but would have required the developer to set aside 25% to 40% of the total buildable area for a dedicated land application system. In addition, effluent management via dedicated spray irrigation systems in the North Carolina coastal plain typically requires between 40 and 90 days of storage for wet weather periods.

Irrigating common areas or individual lots with advanced tertiary effluent was a viable but expensive alternative and required between 40 and 90 days of wet weather storage. These storage basins also would have been difficult to design into the communities because their widely fluctuating water levels would make them aesthetically unattractive.

After extensive soils mapping, geotechnical evaluations, pump testing, and aquifer modeling, direct groundwater discharge to shallow surficial aquifers was selected as the most viable solution. In each case, the groundwater infiltration basins could be designed as site amenities, as long as special precautions were taken to prevent the normal pool elevation from fluctuating more than 15 cm (6 in.) in elevation. The infiltration basins are both functional and attractive. They eliminate the need for wet weather storage because the reclaimed water moves directly into the underlying surficial aquifer regardless of natural precipitation, thereby functioning year-round. The basins also increase property values by creating additional waterfront lots.

Wastewater Characterization and Treatment Process Selection

Since wastewater would not be available for testing until the development was at least partially built-out, it was necessary to estimate influent waste loading based on actual loading from existing, similar communities. In all cases, it was assumed that the raw wastewater generated at each new community would be typical "municipal strength" (see Table 1, p. xx) that would be treated to an acceptable effluent water quality for groundwater discharge (see Table 2, p. xx).

The wastewater treatment and reclaimed water utilization system at each site includes influent screening, an influent equalization basin, a BNR system, an MBR, a UV disinfection system, a lined 5-day reject pond to temporarily store non-complying effluent prior to re-treatment, an odor control system, reclaimed water pumping station, reclaimed water distribution system, two or more infiltration basins, groundwater collection and pumping systems, a groundwater spray irrigation system, control building, access road, and electrical and control systems.

The two BNR processes utilized in the designs included a three-stage MBR package plant by Siemens Corp. (New York) and a batch membrane bioreactor by Aqua Aerobic Systems Inc. (Rockford, Ill.). In each case, microfiltration would be utilized after BNR to remove particles down to 0.05 µm in size and serve as a physical barrier to bacteria, *Giardia*, and *Cryptosporidium* oocysts. The high-quality product water produced by MBRs is fully compliant with regulatory requirements for beneficial use. The finished reclaimed water is subjected to UV disinfection, and sodium hypochlorite is added to the finished water to inhibit regrowth. This process creates multiple barriers to reliably and consistently remove oxygen-consuming organics, suspended and colloidal solids, nitrogen and phosphorus, and pathogens.

Each MBR facility was designed with dual, aerobic digesters to stabilize and provide 45 days storage for biosolids produced by the process. Waste activated sludge (WAS) is periodically pumped to the aerobic digesters to be continuously aerated and mixed. After several waste cycles, the operator can temporarily deactivate the aeration system, allow solids to settle, and decant the supernatant (via telescoping valves) back to the influent pumping station. This decanting process allows the operator to thicken sludge from ¾% solids to 2% or 3% solids. The thickened Class B biosolids are periodically transferred from the first digester to the second digester, which functions as an aerated sludge holding tank for short-term storage (45 days) and further stabilization. Upon documentation of 38% volatile solids reduction, the Class B digested biosolids are transferred to tank trucks and land-applied to permitted agricultural fields.

All the unit processes, including the MBRs and digesters, are covered, and the off-gas is treated via a centralized absorptive odor control system. Appurtenant to the MBR treatment facility is a new control building containing an operator office, analytical laboratory, restroom, electrical room, and chemical storage and feed rooms.

Xpress MBR Package Plant

Three of the six satellite MBR systems designed by McKim & Creed utilized these MBR package plants manufactured be Siemens, which are modular, factory-assembled, three-stage BNR processes. In this system, the combined wastestream is pumped from an inline flow equalization basin and enters the first BNR stage, the primary anoxic cell, where denitrifying microorganisms convert nitrate-nitrogen (produced in the subsequent aerobic process and continuously recycled back to the primary anoxic basin) in the absence of elemental dissolved oxygen (DO) and in the presence of carbon (influent biochemical oxygen demand). The denitrified mixed liquor then flows over a weir into the second-stage aerobic basin.

Microorganisms in the aerobic stage convert wastewater organics to biological cell mass in the presence of DO and convert biological nitrogen to ammonia-nitrogen. At the same time, other aerobic organisms in the mixed liquor convert ammonia-nitrogen to nitrate. The supervisory control and data acquisition (SCADA) system automatically controls positive displacement blowers and adjusts airflow to fine-bubble diffusers located along the bottom of the aerobic basin. This system automatically maintains DO concentrations to within the operator-selected range (typically 2.0 to 3.0 mg/L). A portion of the nitrate-laden mixed liquor is continuously recycled — at typically three to seven times the influent flowrate — back to the primary anoxic basin for denitrification.

Forward flow from the aeration stage is pumped into the membrane operating tanks for liquid–solid separation. Biosolids are separated from the liquid via microfiltration using submerged hollow-fiber membrane technology. The membranes are grouped in modules and potted on the top and bottom to create a leak-proof seal. These modules hang in racks directly in the mixed liquor in each membrane operating tank.

Solids created in the biological treatment process are separated from the reclaimed water via an outside-in filtration process. Using the vacuum produced by the downstream reclaimed permeate pumps, reclaimed water is drawn continuously through the individual hollow-fiber membranes. The membranes remove solids and colloidal particles down to 0.05 micron in size (pathogenic bacteria, protozoa, and nematodes) via filtration, thus providing the first barrier to pathogens.

The mixed liquor in the membrane tanks is continuously mixed and aerated via a coarse-bubble sparger system located below the individual membrane modules. The aeration system is designed to produce turbulent flow conditions in the membrane tanks to scour thickened solids off the outside surfaces of each hollow fiber as water is drawn through the membrane, and the jet system further provides two-phase mixing of mixed liquor and air within the membrane basin and ensures even distribution. As a result, the suspended solids concentration in the membrane tank increases up to 10,000 mg/L.

A second barrier to pathogens happens when membrane permeate is exposed to UV light, resulting in the genetic deactivation of any residual bacteria, viruses, or pathogenic cysts. Disinfected permeate then flows via gravity into the reclaimed water pumping station. The third barrier to pathogens is chlorination, which serves as a backup if the UV system malfunctions. In addition, chlorination serves as a deterrent to biological re-growth in the pumping station and reclaimed water transmission lines. .

The SCADA system paces the sodium hypochlorite feed pumps to maintain a free chlorine residual concentration between 0.5 and 0.75 mg/L prior to discharge into the infiltration basins. In addition, the SCADA system automatically monitors reclaimed water turbidity at the discharge point to confirm that the reclaimed water turbidity never exceeds permit requirements. In the unlikely event that turbidity exceeds 10 NTU, the reclaimed water is automatically diverted back to the 5-day lined upset basin for re-treatment. The reclaimed water pumps are controlled by the SCADA system and convey reclaimed water to the two infiltration basins to maintain a preset “normal pool” elevation.

Aqua Aerobic MBR Batch Process

This unique MBR system operates in a similar fashion to a conventional sequencing batch reactor (SBR), in that influent wastewater is directed to only one basin at a time. While the first basin is filling, the second basin undergoes alternating anaerobic, anoxic, and aerobic cycles for BOD oxidation and BNR. The system includes both fine-bubble diffused aeration and floating direct-drive mixers. This combination makes it possible to optimize BNR by separating the aeration function from the ability to maintain solids in solution. The entire process is fully automated. Another advantage of batch technology is that it is not necessary to construct a separate influent flow equalization basin; equalization volume can be readily incorporated into the individual SBRs.

Unlike a conventional SBR, however, the Aqua Aerobic batch MBR process lacks the classic settle, decant, and waste cycles. Instead, mixed liquor is pumped directly into the adjacent membrane tank at the end of the biological cycle, where submerged microfiltration membranes function as a liquid–solids separation process. Solids are separated from the reclaimed water via an outside-in microfiltration process using Puron hollow-fiber membranes. These membranes are individually sealed at the top, and membrane bundles are potted in fiberglass at the bottom only.

This arrangement allows fibrous material to flow freely upward, along the membranes and out from between the fibers, and back into the mixed liquor. Top-potted membrane bundles, however, tend to collect fibrous material at the top, resulting in increased fiber breakage.

Like the Siemens MBR design, permeate is drawn continuously through the individual hollow-fiber membranes via a vacuum produced by the permeate pumps. Puron membranes remove solids and colloidal particles down to 0.05 micron, thus physically removing 100% of pathogenic bacteria, protozoa, and nematodes. The membrane operating tank functions similarly to the Siemens system, in that it is continuously mixed and aerated via a coarse-bubble sparger, which is integral to the lower membrane header. Solids are automatically wasted from the system during each cycle.

The downstream unit processes — including UV disinfection, continuous monitoring, and chlorination — are accommodated similarly to the Siemens system. The SCADA-controlled pumps convey the reclaimed water to one or more groundwater infiltration basins.

Groundwater Infiltration Basins

The reclaimed water is used to maintain the water level in two or more unlined, earthen basins dug in soils capable of infiltrating the entire average daily reclaimed water production volume (at design conditions), even during peak wet-weather season. The basins' footprints range from 0.4 to 0.8 ha (1 to 2 ac) with a length-to-width ratio of 4:1 or greater. Loading rates vary with specific soil permeability but range between 0.08 and 0.7 $L/d \bullet m^2$ (0.23 and 2 $gal/d \bullet ft^2$) for the six projects.

The developer's landscape architect worked with the engineer to create natural-looking basins that enhance the beauty of the site. Ample green space, surrounding the infiltration basins, provides an added level of security that allows the basins to surcharge during wet weather by as much as 0.9 m (3 ft). Gently sloping grassed overbanks create parklike areas that can be enjoyed by residents during dry weather but that can be flooded on a short-term basis during peak wet weather.

For additional reliability, perforated groundwater collection systems completely encircle each infiltration basin and are connected through an electrically actuated valve to a groundwater pumping station. This system allows groundwater levels to be automatically lowered during wet weather to prevent excessive mounding under the basins.

Remote Basin Monitoring and Liquid Level Control

The reclaimed water pumps maintain liquid levels in the infiltration basins via a feedback control loop through the plant programmable logic controller (PLC) and SCADA system. The PLC automatically monitors water levels in the infiltration basins to verify that it does not exceed the normal high water level. The PLC then initiates a dosing cycle starting with the first infiltration basin by opening its fill valve and closing the valves to the other basins. The PLC continuously monitors the reclaimed water totalized flow until the entire dose volume has been delivered, at which time the PLC opens the next infiltration basin fill valve and closes the current fill valve. The process repeats with each subsequent infiltration basin until the cycle is complete, at which time the cycle begins again with the first basin.

If the liquid level in one or more of the basins fails to return to normal before the next dosing cycle (such as following a significant rainfall event), the PLC automatically opens the groundwater collection system control valve and allows groundwater to flow to the pumping station. As liquid level rises in the pumping station, the submersible pumps are activated to draw down groundwater in the vicinity of the infiltration basins. The pumping station discharges the excess groundwater into one or more amenity lakes that overflow to adjacent wetlands during wet weather events. As the liquid level falls in the groundwater pumping station, a differential head is created, causing flow toward the perforated drain network and a net decline in the water table elevation. This change in the elevation creates a higher driving head in the infiltration basins, thus increasing the infiltration rate and creating a subsequent decline in basin water level. The system automatically resets once the liquid in each basin reaches normal pool elevation.

During the dry season, when natural groundwater elevation declines, the liquid level in the infiltration basins and adjacent natural wetlands may begin to fall below the normal pool elevation even with reclaimed water dosing. One or more 60-m-deep (200-ft-deep) gravel-packed groundwater wells at each site supplement reclaimed water to maintain normal pool elevations even during droughts. If, following a reclaimed water dose, the water surface falls below the normal pool elevation, the PLC will automatically activate the supplemental well pump to convey groundwater into the basin.

Fast Permitting, Construction

The state of North Carolina offers an "express" review process for non-discharging systems that made it possible for McKim & Creed to design and obtain permits for the new treatment works, infiltration basins, and associated infrastructure within 6 months from the date of the owner's notice to proceed.

After permitting, bids were solicited from general contractors for the construction of the wastewater treatment facility, reclaimed water dispersal systems, and associated infrastructure. The time required to construct the new facilities typically ranges from 12 to 15 months from the date of the notice to proceed.

Construction costs varied depending on the level of treatment and the system design capacity (see Table 3, p. xx). While the capital cost of MBR technology is higher than conventional activated sludge processes, the unique multiple-barrier approach to treatment offers a strong safeguard against treatment upset, pathogen release, or contaminant breakthrough. In addition, the MBRs significantly reduced the treatment facility footprint, freeing up high-value land for additional residential lot sales.

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Table 1. Projected Influent Parameters

Influent parameter	Flow or contaminant concentration
Flow	
Average day design influent	0.1 mgd to 0.5 mgd
Peak day flow peaking factor	2.0
Peak hour flow peaking factor	2.5
Carbonaceous biochemical oxygen demand concentration	225 mg/L

Total suspended solids concentration	240 mg/L
Total nitrogen concentration	40 mg/L
Total phosphorus concentration	7 mg/L

Table 2. Finished Reclaimed Water Quality

Effluent parameters	State effluent standard for direct groundwater discharge	Finished reclaimed water quality
Flow		
Average day effluent	—	0.1 to 0.5 mgd
Peak day flow peaking factor	—	2.0
Peak hour flow peaking factor	—	2.5
Carbonaceous biochemical oxygen demand concentration	< 10 mg/L	< 5 mg/L
Total suspended solids concentration	< 5 mg/L	< 5 mg/L
Total nitrogen concentration	< 4 mg/L	< 4 mg/L
Total phosphorus concentration	< 2 mg/L	< 2 mg/L
Turbidity	< 10 NTU	< 0.2 NTU
Fecal coliforms	14 CFU/100 mL	Nondetect

Table 3. Construction Costs for Reclaimed Wastewater Treatment and Dispersal Systems (0.15 to 0.5 mgd)

Component	Cost
5-day lined earthen upset basin:	$0.75 to $2 per design gal/d
Membrane Bioreactor with BNR:	$12.50 to $16.00/ design gpd
Odor Control (including tank covers):	$ 1.50 to $ 2.50 / design gpd
Control Building:	$ 0.65 to $ 1.50 / design gpd
SCADA/Instrumentation/Telemetry:	$ 1.75 to $ 2.50 / design gpd
Class B Biosolids Digestion & 45 days Storage	$ 2.25 to $ 3.00 / design gpd
Reclaimed Water Infiltration Basins & Groundwater Control System	$ 3.25 to $ 4.50 / design gpd
Total	**$22.65 to $30 per design gal/d**
Average cost per residential lot	***$9000 to $12,800***

SCADA = supervisory control and data acquisition system.