FINAL REPORT

Pilot Testing of ULTRAFILTRATION For Low Level Phosphorus Removal

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EXECUTIVE SUMMARY

As part of the Chemical Treatment Followed by Solids Separation (CTSS) Supplemental Technology Demonstration Project carried out by HSA at the Everglades Nutrient Removal (ENR) Project site in 1999, a number of vendor technologies were evaluated (*see*, HSA's CTSS Report to the South Florida Water Management District (SFWMD) for further detail). One of the vendor technologies evaluated was ultrafiltration (UF). The UF unit tested was a relatively small (sub-plot scale) unit capable of producing a permeate flow of 1 gpm at a 90 percent recovery rate (*i.e.*, 1 gpm of permeate from a feedwater flow of 1.1 gpm). The nominal pore size of the UF membrane was on the order of 0.03 um. The small unit was tested for direct treatment (no chemical addition) of ENR effluent (Post-STA) over a four-week period and consistently produced a permeate of less than 10 ppb of Total P treating a feedwater varying from 17 to 39 ppb of Total P.

Based on the promising results obtained with the small unit (*i.e.*, permeate Total P consistently less than 10 ppb), it was apparent that additional larger scale testing of UF was warranted. SFWMD decided to carry out the additional work as an addendum to DB Environmental Laboratories (DB Labs) Submerged Aquatic Vegetation (SAV) Project. Accordingly, a proposal was made to DB Labs and SFWMD to carry out a larger scale UF pilot-testing program.

Description of Ultrafiltration (UF) Process

"Ultrafiltration" is a pressure-driven, separation process where the water to be treated is separated by a porous membrane into a stream of purified filtrate/permeate and a remaining quantity of concentrate. The principle of UF is that in the presence of an external pressure or driving force, liquid flow occurs from the concentrated solution to the dilute solution across a semi-permeable membrane. The pure water (known as "product water" or "permeate") essentially emerges at near atmospheric pressure. Particulate solids contained in the water that have been rejected by the membrane are accumulated in the concentrate stream.

UF plants can be operated either in dead-end or cross-flow modes. An important difference is the direction of the flow relative to the membrane layer. In dead-end systems, all the feed flow passes through the membrane. The separated particles are concentrated at the upstream side of the membrane. This system is typically applicable for waters with low solids concentration allowing a high packing density of the membranes. Cross-flow systems, on the other hand, are more suited to treat waters with higher influent solids content. The feed flow in these systems is parallel to the membrane layers allowing only a certain portion of the feed water to pass through the membranes. Consequently, the separated particles are removed from the membrane surface with the unfiltered water flow resulting in a diluted concentrate.

Objectives

Objectives of the larger scale UF pilot testing program were to:

- Develop process design criteria for the UF technology that would enable a cost analysis to be made for full-scale application of the technology; and

- More fully characterize the effluent and concentrate streams produced by a UF system.

Description of Pilot Test Facilities

The pilot UF treatment process employed (1) low lift pumping, (2) cartridge filtration, (3) flow equalization, (4) booster pumping, and (5) membrane separation. ROCHEM Environmental, Inc. (ROCHEM) supplied the UF systems tested at the South ENR (Post-STA) Test Site. While the smaller unit was operated in the cross-flow mode, the larger pilot treatment unit was designed to operate in the dead-end mode. Both units were tested without the addition of treatment chemicals. The “end of a filter run” is defined when the operating pressure exceeds a preset value, at which point the membrane(s) required cleaning.

Smaller Pilot Unit:

Typical operating parameters for the ROCHEM UF cross-flow mini-plant (Type CF-UF1-3) were:

Operation mode:	cross-flow
Set flow rate:	2 gpm (0.45 m^3/h)
Permeate yield:	90%
Membrane area:	3 m^2
Nominal pore size:	50,000 Dalton (nominal 0.03 μm)
Max operating temperature:	104°F (40°C)
Operating pH range:	3-11
Max operating pressure:	29 psi (2.0 bar)
Electrical power:	0.5 HP (4 kw)

Larger Pilot Unit:

The larger ROCHEM pilot plant (Model No. B2006) was equipped with two module blocks, each block containing three parallel membrane modules. The total membrane area of the unit was 60 m^2 (10 m^2 per module). Accumulation of solids in operating UF units typically results in increasing pressure drop through the membrane layer. In order to provide essentially constant permeate flow, the ROCHEM design automatically compensates (*i.e.*, increases) the operating pressure during a filtration cycle. The plant allows simultaneous normal operation of one block while the other block of three modules are cleaned. The permeate of an operating block is used for flushing the exhausted filter modules. While a cleaning cycle is automatically initiated upon reaching the pre-selected cut-off pressure, the optimum cleaning duration is determined for each application. Based on the prior experience with Post-STA waters with the smaller UF unit, ROCHEM suggested a 5-minute cleaning period. During flushing, the boosted permeate of the operating block is supplied with air introduced to the upstream side of the membranes to remove concentrated particles. Near the end of a cleaning cycle, a short duration cross-flow flush is initiated. The amount of permeate consumed for cleaning is about 5 percent of the total flow. In addition to routine water-air mix cleaning, UF units need chemical cleaning on a less frequent but regular basis. Typical operating UF parameters for the larger unit are listed below:

Operation mode:	dead-end
Capacity:	24.3 gpm (5.5 m^3/h)
Permeate yield:	90-95%
Membrane area:	60 m^2
Nominal pore size:	50,000 Dalton (nominal 0.03 μm)
Max operating temperature:	104°F (40°C)
Operating pH range:	3-11
Max operating pressure:	29 psi (2.0 bar)
Electrical power:	9.4 HP (7.0 kw)

Sampling and Analytical Procedures

For the smaller UF unit, a condensed monitoring program was conducted involving collection of samples of the feed and permeate, and analyzing the samples for phosphorus forms only.

The larger UF unit was monitored more intensively with 24-hour composite samplers located on the influent and permeate, and grab composite samples being collected from the concentrate or backwash. Operational data were collected and recorded for the larger pilot unit, including:

- Elapsed run time;
- Flow rate through each module;
- Feed, permeate and concentrate pressures;
- Feed water temperature;
- Cleaning interval; and
- Cleaning chemical utilized (acid or caustic).

Testing for the smaller UF unit was carried out over the period of October 13 to December 7, 1999, whereas the testing for the larger unit was conducted from February 7, 2000 to April 28, 2000.

Results and Discussion

Raw water (Post-STA) Total P concentrations varied from 11 µg/L up to 70 µg/L during the study period. Including two values in excess of 60 µg/L, the average raw (Post-STA) water Total P concentration in the June 3, 1999 to December 23, 1999 period was 21.5 µg/L with a standard deviation of 7.7 µg/L. Corresponding values for the February 7, 2000 to April 13, 2000 period were 34.7 µg/L and 6.7 µg/L, respectively. Due to seasonal effect or some other condition such as increased hydraulic loading to the ENR, Total P values were significantly higher in the February 7 to April 13, 2000 period than in the last six months of 1999.

When assessing temporal UF influent and effluent (permeate) Total P concentrations for periods of UF testing, the data was segmented into three distinct periods. The first period represents the operation of the smaller pilot treatment unit from October 13, 1999 to December 7, 1999. On average, a 17 µg/L raw water Total P concentration was reduced to 6.4 µg/L by the smaller pilot UF unit. The larger scale pilot UF plant was tested from February 7, 2000 to April 28, 2000. Data in this second period (February 7, 2000 to April 28, 2000) shows that the average Total P concentration of 33.2 µg/L was reduced to 24.9 µg/L by the larger pilot UF unit. While maintaining normal operation, Total P removal efficiencies were higher in the April 2, 2000 to April 28, 2000 period. In this last period, the average Total P concentration of 30.3 µg/L was reduced to 13.6 µg/L with several individual effluent data points recording less than a Total P of 10 µg/L. Total P removal efficiency of the smaller unit exceeded the average Total P removal of the larger pilot unit (68 percent versus 39 percent). The data also shows that Total P removal efficiency of the larger pilot unit was higher in the second part (third period) of its operation (55 percent versus 25 percent).

Average influent SRP concentrations were 3.0 µg/L, 10.0 µg/L, and 3.1 µg/L during the same three segments of time listed above. The corresponding UF effluent Total P concentrations were 6.4 µg/L, 24.9 µg/L, and 13.6 µg/L, respectively. These data show higher Total P removal at reduced concentrations of influent SRPs. This is to be expected since UF will remove only particulate and colloidal P exceeding the membrane pore size. SRP will not be removed to any degree.

Influent TDP concentrations were 11.8 µg/L, 26.1 µg/L, and 14.2 µg/L in segments 1, 2 and 3, respectively. Corresponding average effluent Total P concentrations were 6.4 µg/L, 24.9 µg/L, and 13.6 µg/L, respectively.

The observed differences in percentage of Total P removal by the two pilot units probably has little to do with configurational differences, but is due to changing feedwater characteristics. During time periods the STA effluent was discharging low Total P concentrations (*i.e.*, 25 µg/L or less) and virtually no SRP (*i.e.*, less than 4 µg/L of SRP), the UF technology was able to produce an effluent containing less than 10 µg/L of Total P. During periods of higher TDP and SRP, the UF effluent Total P concentration was greater than 10 µg/L.

Water Quality Testing

During the larger UF pilot testing, samples were collected of raw water, filtrate, concentrate and spent cleaning solutions and were submitted to the contract laboratory for metals, nitrogen series, TDS, common cations and anions, and TOC. No significant differences (*e.g.*, less than 20 percent difference) were observed in feed versus filtrate (effluent) average sample results for the following constituents:

Aluminum
Chloride
Sodium
TKN
Iron
Molybdenum
Zinc
Alkalinity
Color
Specific Conductance
TOC
Magnesium
Nitrate
Total Dissolved Solids
Calcium
Dissolved Silica
Sulfate
Total Solids
Mercury
Potassium
Total Suspended Solids

> *Ammonia*: The UF treatment system removed on average approximately 30 percent of the influent ammonia during the pilot testing. Average ammonia was reduced from 0.112 to 0.079 mg/L.
>
> *Manganese*: The UF treatment system removed on average approximately 50 percent of the influent manganese during the pilot testing. Average manganese was reduced from 13 to 6.6 mg/L.

Samples were collected of the concentrate stream after completion of a backwash cycle. The concentrations of ammonia and manganese in the concentrate are greater than the corresponding effluent concentrations. There were no significant differences (*e.g.*, less than 20 percent difference) observed in concentrate versus feed or filtrate concentrations for the remainder of the parameters tested.

HSA collected UF feed and effluent samples during the week of April 3, 2000, for bioassay and AGP analyses. Feed and filtrate samples were collected simultaneously to determine if any observed effects were the result of the feed waters or from the UF treatment process. Exposure to the UF feed water significantly reduced the survival of the Bannerfin Shiner however, there was no adverse effect caused by exposure to the UF filtrate.

Conceptual Design and Preliminary Cost Estimate for a Full-Scale Ultrafiltration Application

Flow and Total P data used in developing facility conceptual designs are required, by the standard of comparison guidelines, to be developed from the 10-year period of record (POR) baseline data used for preparing the detailed design for STA 2. The STA 2 flow and phosphorus concentration data were provided by SFWMD. The POR for the data series is from January 1, 1979 through September 30, 1988. The historical flow weighted mean Total P concentration for the POR was equal to 122 mg/L.

The UF process was only tested on Post-STA waters (Post-BMP waters typically contain significant amounts of SRP that the UF technology does not remove) and the conceptual design for a full-scale treatment facility is based on the scale-up of the pilot data collected for the testing period. Accordingly, a UF conceptual design was only developed for the Post-STA treatment scenario.

Baseline STA 2 effluent flow (Post-STA) for the 10-year POR is equal to 536 acre-feet per day (175 million gallons per day [mgd]).

The STSOC guidelines require facilities to be designed to achieve flow weighted average effluent Total P concentrations of 10 ppb and 20 ppb Total P with 0 percent, 10 percent, and 20 percent flow diversion (STSOC required) of the 10-year POR flow volume. The UF pilot testing showed that UF could produce a treated effluent of less than 10 μg/L Total P when SRP levels in the influent were in the range of 5 μg/L. However, based on the larger pilot trials, UF when treating Post-STA water may be expected to consistently produce an effluent Total P in the order of 20 μg/L. For this reason only one scenario was evaluated for UF (*i.e.*, a treatment system producing a flow weighted effluent Total P concentration of 20 ppb with 20 percent diversion of flow volume).

The wide fluctuations of flows associated with the EAA stormwaters will require full-scale water treatment systems to be coupled with flow equalization basins (FEB) in order to store runoff from peak rainfall events until it can be adequately processed. For purposes of this Report, flow equalization was assumed to be accomplished within the STA. A water balance was completed to determine the most effective size of the FEB and the treatment plant. The assumptions and the basis for the balance are summarized below:

- "Natural treatment," flow equalization, and UF treatment would occur within the footprint of the existing STA 2. Based on the pilot data, it was estimated that the UF treatment process could treat Post-STA water with an outflow Total P concentration to 65 ppb.

- The required size of STA 2 acres to provide an effluent Total P concentration of 65 ppb was estimated using an exponential decay relationship between the STA 2 area and the outflow

Total P concentration. This relationship is represented by C=Co*e-^{kA} ("C" is the outflow concentration, "Co" is the inflow concentration, "K" is a constant, and "A" is the STA area). Using the assumed inflow concentration (122 ppb) and the outflow concentration (50 ppb), the exponential relationship becomes, 50=122e-^{kA}. If the UF plant would treat Post-STA water with an outflow concentration of 65 ppb, a preceding 4,540-acre "natural system" would be required.

- The Post-STA full-scale conceptual design uses Cell No. 2 and Cell No. 3 of STA 2 (combined area of 4,440 acres) as a "natural system."
- 1,500 acres of STA 2 will be used as a FEB. The levees will not be modified and will be used to store water up to a maximum depth of 4.5 feet.
- Bypass will occur when the FEB has reached capacity.
- Rainfall and evapotranspiration from FEB were not considered.
- Total P removal within the FEB is estimated at 20 percent.
- The full-scale UF system would be able to operate at a peak hydraulic capacity of 50 percent greater than its average daily design flow rate for short time periods.
- The UF technology would produce an average effluent Total P concentration of at least 0.02 mg/L as P.
- Full-scale treatment scenarios were based on a scale-up of the UF pilot data.

The water balance calculations resulted in a treatment facility sized for an average flow rate of 95 mgd. The Post-STA conceptual design scenario was based on using 4,400 acres of STA 2 as a "natural system." The natural system would produce an average effluent Total P concentration of 65 ppb. Flow equalization would occur in a 1,500-acre basin and the remaining 530 acres for the treatment plant works and backwash solids and chemical cleaning lagoons. The existing influent STA pump station would pump the water into the STA for wetland treatment. A new pump station would be installed to pump the naturally treated water into the FEB. Another new pump station would be installed to pump the water from the equalization basin into the UF treatment plant.

SFWMD provided unit costs for selected capital, operation and maintenance (O&M), replacement and salvage items. These unit costs were used to prepare a cost estimate for the 95 mgd full-scale UF treatment facility treating Post-STA waters. "The Basis for Cost Estimates of Full-Scale Alternative Treatment (Supplemental) Technology Facilities" (August 1999), prepared by Brown and Caldwell

Engineers (B&C) for SFWMD, was also used to source various unit costs and is referenced where appropriate.

Conclusions developed from the operation of the UF pilot unit include the following:

- The UF treatment technology employed during the pilot unit operations was found to reduce phosphorus, contained in representative Post-STA waters, to less than 20 micrograms of P per liter on a routine basis. UF, without chemical addition, could not be expected to produce an effluent Total P of less than 10 μg/L unless influent SRP concentrations could be consistently maintained below 4 ppb.

- With 20 percent flow diversion, the UF technology, coupled with a natural treatment component and a flow equalization basin, can reduce the incoming phosphorus load to a level that routinely produces a treated effluent of less than 20 micrograms of P per liter.

- The UF technology appears to produce no adverse impact on downstream flora and fauna based upon bioassay toxicity testing and only limited changes in the water quality were observed.

- Excluding the cost of the existing STA, which will be used as the flow equalization basin, the total capital cost of the 95 mgd full-scale facility would be equal to approximately $75 million dollars, with annual operating costs of approximately $5,840,000.