Microfiltration Pilot Studies For Aquifer Storage and Recovery Pretreatment

Clint Noble, Terry Horan, Edwin Brown, Mark Shaffer, and Jose Lopez

The United States Army Corps of Engineers, in conjunction with the South Florida Water Management District (SFWMD), has initiated surface-water treatment pilot studies as part of the Comprehensive Everglades Restoration Program (CERP). These pilot projects are aimed at determining the technical and economic feasibility of treating surface water for the aquifer storage and recovery (ASR) program. This article deals with a project that investigates the treatability of surface waters at the Lake Okeechobee/St Lucie Canal intersection (Port Mayaca Lock) using microfiltration and cartridge filtration technologies as methods of pretreatment prior to discharge into an ASR well.

Two different filtration techniques were tested: a skid-mounted microfiltration test unit supplied by the US Filter Memcor Division and a serial cartridge filtration system supplied by Ionics Corporation. A process flow diagram showing the configuration of these two pilot systems at the Port Mayaca Lock test site is shown in **Figure 1**.

The full-scale implementation of these technologies will depend on:

- Filtrate water quality relative to fecal coliform and turbidity (<0.3 NTU)
- Extent of pathogen removal without chemical or ultraviolet (UV) disinfection
- Filtering process efficiency (i.e., maximum sustained flux rate)
- Cleaning chemical usage rates
- Electrical consumption
- Optimal feed flow rate in terms of gallons per square foot of membrane area per day (GFD)
- Residual solids production rate
- Ease of system maintenance
- Capital costs for a 5-million-gallon-per-day (MGD) system

The fundamental measure of full-scale filtration feasibility will be based on the resulting cost of the selected filtration system that is consistently producing acceptable water quality at the highest possible sustained hydraulic throughput.

Microfiltration Overview

The microfiltration process is a physical solids separation technique capable of removing small particulate matter and suspended solids ranging from 0.04 to 20 microns in diameter. The essence of microfiltration is in its use of membrane technology. Membranes, the filtering media, act as finely porous barriers, allowing only particles of a certain size to pass, making them semi-permeable. Commercially available microfiltration membranes are made from a variety of materials, including organic polymers (polypropylene), ceramics, and metal alloys.

Microfiltration membranes can remove large macromolecular substances such as humic acids, clays, and silt from a fluid stream in addition to most algae and bacteria. Low-molecular-weight compounds and common inorganic constituents are typically not removed and pass directly through the membrane.

Microfiltration has a technical advantage over conventional water treatment processes via the ability to remove particulates up to an order of magnitude smaller in diameter (0.04 microns). As a result of this small pore size, bacteria, viruses, and parasitic cysts are essentially completely removed without disinfection.

Microfiltration Mechanism

In this microfiltration study, a "dead-end" process filters all the incoming feed water. Accumulated solids are trapped on the surface of the membrane until backwashing is performed. During backwashing, accumulated solids are flushed away from the membranes and are collected for disposal. Typical backwash volumes represent between 2 and 5 percent of the total influent stream.

Clint Noble is a project geologist with HSA Engineers and Scientists. Terry Horan, P.E., is a project manager with HAS Engineers and Scientists. Edwin Brown, P.E., and Mark Shaffer, P.E., are environmental engineers with the Jacksonville District of the U.S. Army Corps of Engineers. Jose Lopez, P.E., is a lead engineer for the South Florida Water Management District.

Solids accumulate rapidly on the surface of the membranes, gradually plugging the system and increasing feed pressures. The rate of this increase is related to the size and concentration of solids within the feed stream and the amount of flow through the membrane.

Routine flux restoration is achieved by backwashing the solids from the membranes, reducing feed pressure. For the Memcor microfiltration system, backwashing is accomplished by pressurizing the inside of the tubular membranes with compressed air and rapidly flushing water across the outside of the membranes.

The productivity or efficiency of microfiltration membranes is usually measured by

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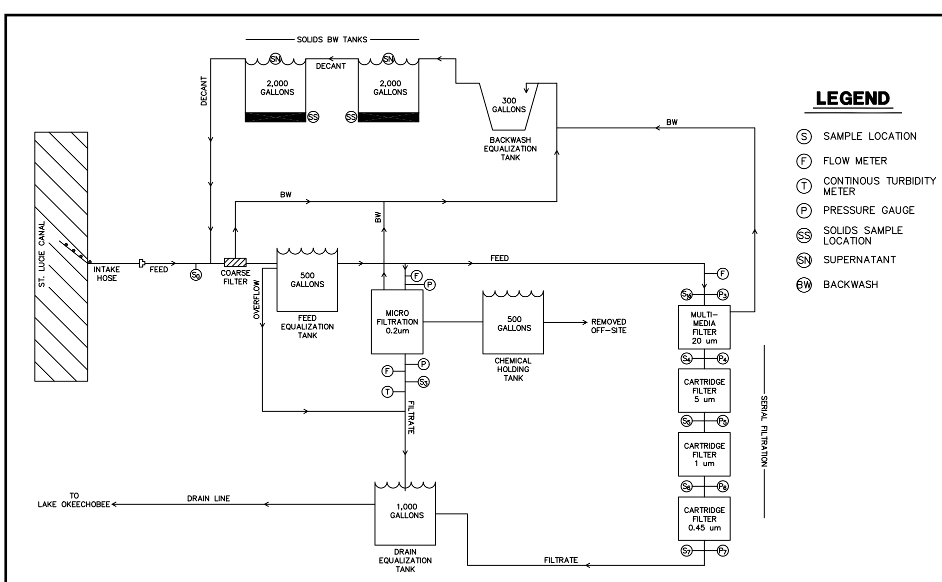

Figure 1. Schematic Flow Diagram of Pilot System

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the amount of flow that can pass through a unit area of membrane surface, often referred to as the flux rate. Flux rates are commonly measured in units of gallons of flow per square foot of membrane per day (GFD). Average GFD values for organic polymer membranes vary from 25 to 50. GFD for a particular membrane is dependant upon backwash intervals and the chemical composition and solids load of the feed streams.

Advantages of Microfiltration Applicable to ASR

There are several technical and cost-beneficial advantages of using microfiltration as a pretreatment for ASR:

- There is absolute 100-percent removal of coliform bacteria and related pathogens from feed streams.
- Capital and O&M costs are competitive with conventional water-treatment techniques (coagulation, flocculation and filtration).
- Filtrate water turbidities are generally around 0.1 NTU.
- The technology has been successfully demonstrated for treating South Florida (EAA) stormwater for phosphorus removal (**www.hsa-env.com**).
- The process is energy efficient, due to relatively low feed-water pressures (20-40 psi) and the lack of phase change during filtering (as in distillation).
- Residual solids quantities are low and nonhazardous (as opposed to using conventional chemical and flocculation treatments) and can be used in land application.
- Automation—Normal operation, chemical cleaning, and backwashing procedures are almost completely automated and require minimal operator training. The system can be automated to shut down in cases of pH, pressure or temperature problems.
- Expansion—The modular character of the membrane system design makes it practical to expand in the future while meeting present needs.
- Technological advantage—Each membrane process has specific capabilities that permit certain applications which would not be possible otherwise.
- Start-up time is short, usually less than a half hour.
- Clean In Place—Because of the modularity of the membrane system, it may not be necessary to shut down the entire system for cleaning.

Disadvantages of Membrane Technology

The primary disadvantages of membrane technology include:

- Fouling—All membranes eventually foul, and prefiltration and other foul-reduction methods are usually needed. Periodic chemical cleaning is needed to restore flux and may leave units off-line for long periods of time.
- Limitations of membrane materials—The membrane must be chemically compatible with the feed stream. New high-performance membranes are expensive.
- A perceived limitation is cost, compared to more conventional filtration technologies. Since costs have been dropping steadily for full-scale installed systems during the last five to seven years, this trend needs to be closely monitored because any gap between conventional filtration and microfiltration has virtually closed. Membrane filtration costs are anticipated to drop by 10 percent annually over the next several years as the demand continues to expand at an approximate annual rate of 25 percent. Over the last five to seven years, full-scale system costs reported by US Filter have dropped from approximately \$1 per gallon of installed capacity to \$ 0.50 to \$ 0.60 per gallon of installed capacity range, based on a full-scale system size of 5 to 10 MGD.

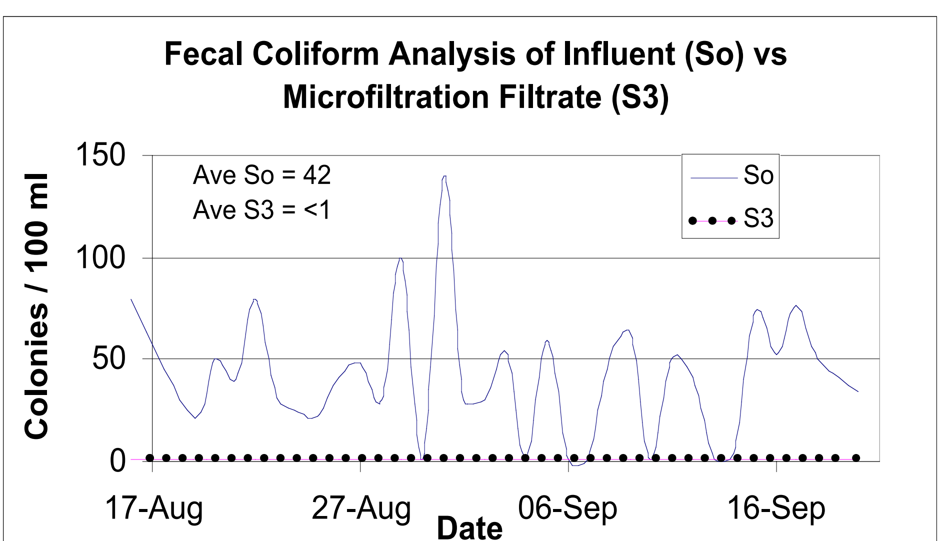

Figure 2. Fecal Coliform Analysis of Microfiltration Filtrate

Description of Pilot Units

Microfiltration Unit Description

US Filter provided a microfiltration pilot unit (Model 3M10C) with a nominal filtering pore size of 0.2 µm at a capacity of 10-20 gallons per minute (gpm). The main components of the unit are the filter modules. The unit contains three intermediate packing membranes (M10V IPD), each housed in its own module. Each module contains thousands of hollow-fiber filtration membranes surrounded by a protective plastic screen sealed at both ends. The membranes are constructed of polyvinylidene fluoride with a 204 ft^2 (612 ft^2 total membrane surface area) hydrophobic surface.

This particular microfiltration unit is a dead-end system. This configuration allows for a direct-flow, pressure-driven system in which the influent water is forced perpendicularly across the fibers of the membrane in an "outside-in" flow direction. The entire influent flow is evenly distributed through the top and bottom of all three modules.

The influent feed pump pressurizes the modules to nearly 30 psi, forcing the water through the hollow-fiber membranes. The permeate is collected as it is forced out from the inside of the hollow fibers. The microfiltration unit is a completely automated, continuously operating, self-cleaning apparatus containing an automatic data logger that records filtrate turbidity, run hours, feed pressure, filtrate pressure, transmembrane pressure (TMP), feed flow, filtrate flow, filtrate totalizer, and information on emergency shutdown conditions.

Multimedia Serial Filtration Unit Description

The serial filtration unit consists of a 20-µm (nominal) multimedia sand filter, followed in series by polypropylene wound-fiber-floss cartridge filters of descending pore size: 5µm (nominal), 1µm (nominal), and 0.45 µm (absolute).

Data Collected and Procedures

Onsite information that was obtained daily during pilot-unit operation included:

- Feed-flow rates and pressure differentials across filter membranes
- Solids production rates
- Feed and filtrate analyses for fecal coliform, turbidity, temperature, conductivity, color, and UV254 absorbance
- Optimized pathogen testing for giardia, cryptosporidium, heterotrophic plate count, E-Coli and fecal coliform

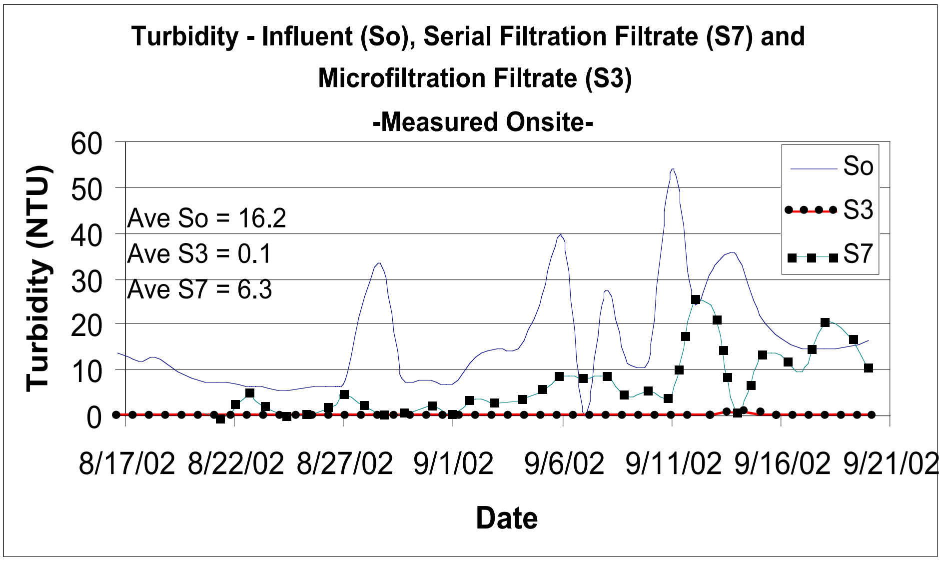

Figure 3. Turbidity Analysis of Influent water and Serial and Microfiltration filtrates.

Harbor Branch Environmental performed the routine daily fecal testing and the city of Tampa's health department laboratory completed the end-of-study pathogen testing.

Pilot Study Results

The pilot filtration facility was operational from August 14 through September 20 for a total of 35 days. The microfiltration unit was operational a total of 755 hours and the serial filtration unit was operational a total of 625 hours.

During the pilot study, microfiltration-process throughput (GFD) and backwash frequency were altered to determine the settings that would produce the highest membrane yields with the longest uninterrupted run times between flux restoration (chemical cleaning). Flux through the serial filtration unit was also varied to determine the highest cartridge yields with the longest uninterrupted run times between flux restorations.

Pilot Units Hydraulic Performance

Microfiltration Hydraulic Performance

The microfiltration pilot unit was continuously operational for 95.5 percent of pilot testing. The unit was down approximately 85 hours during testing as a result of two storm-induced power outages and plumbing repairs on the pilot facility. The microfiltration unit itself did not pose any technical operational upsets and ran efficiently throughout pilot testing.

Highest hydraulic throughput occurred between the second and third chemical cleans, producing approximately 200,000 gallons of filtrate during 343 hours of operation. Optimal membrane throughput was achieved at a flow of 12 gpm and a backwash interval of 20 minutes. During this optimal period, a flux rate of 27 GFD was maintained.

Serial Filtration Hydraulic Performance

The serial filtration unit was operational for 77 percent of pilot testing. The unit was down approximately 205 hours during testing. Approximately 85 of those down hours were the result of the power outages and plumbing repairs described previously.

The remaining 120 hours of downtime were due to technical difficulties regarding the filter cartridges clogging rapidly during times of normal filtration. Specifically, the 0.45-µm cartridge would completely plug up within 20 minutes of filtration at a flux of 10 gpm. When this occurred, pressure backed up across the system and reduced water flow to 5 gpm or less. After the first week of pilot testing, the 0.45-µm cartridge was bypassed, making the 1-µm cartridge the final filter in the serial system.

Filtrate Water Quality Analysis of Pilot Facility

Observed changes in raw-water chemistry during pilot operations are attributed to the variations in the water flow around the Port Mayaca Lock. Prior to September 7, water flowed from Lake Okeechobee to the St Lucie Canal at a rate of about 800 cubic feet per second (cfs). From September 7-9 there was no flow in or out of Lake Okeechobee. From September 10-20 water flow resumed from the lake to the canal, starting at 1,300 cfs on the September 10 and slowing gradually to 52 cfs on September 20.

Fecal Coliform

Fecal coliform of raw canal water varied from less than one to 140 colonies/100ml and averaged 42 colonies/100ml. Throughout the pilot study, no fecal coliform were detected in microfiltration filtrate (see **Figure 2**). On average, the one-micron serial filtration filtrate contained 23 colonies/100ml of fecal coliform. Roughly 50 percent of fecal coliform colonies were removed from the raw influent stream by the serial filtration unit throughout pilot testing.

Turbidity

Figure 3 summarizes daily turbidity values for all sampling locations in the pilot facility. The serial filtration unit reduced turbidity from the raw influent stream by about 61 percent, while the microfiltration unit effectively reduced turbidity from the influent stream by nearly 100 percent throughout the duration of pilot testing, illustrating that the turbidity of the microfiltration filtrate was consistently below the required standard of 0.3 NTU. Typical microfiltration filtrate turbidities were reliably around 0.1 NTU, regardless of the turbidity of the influent stream.

Conductivity

The conductivity of the influent was on average 522 microsiemens/cm. The conductivity of the microfiltration filtrate and the serial filtration filtrate was nearly identical to that of the raw influent stream for the entire study. There was no change in water conductivity through the microfiltration system relative to the feed water.

UV254 Absorbance

The average UV254 absorbance for the feed stream was 0.658 cm^{-1}. The average UV254 absorbance value for the microfiltration filtrate was 16 percent less than the raw influent stream. There was no substantial reduction in UV254 absorbance from the feed and one-micron serial filtration effluent. Data suggests there is no systematic or quantifiable relationship between microfiltration filtrate and feed-water UV254 data.

pH

The average pH of the feed water was 7.66 and remained nearly identical to the pH of the filtrate. There were no appreciable changes in pH through either the serial filtration system or the microfiltration system.

Color

The mean color value of the feed water was 250 Platinum Cobalt Units (PCU) and, on average, color was reduced by 73 percent and 44 percent by the microfiltration and serial filtration units, respectively.

Bacteriological and Parasitic Data

Bacteriological and parasitic analyses of the feed water, microfiltration filtrate and

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Analysis	Ave Raw-Water Value	Units	%Removal Microfiltration	%Removal Serial Filtration
E. Coli	55	col/100ml	100	25
Enterococci	207	col/100ml	100	21
Giardia/Crypto	None Detected	cysts/100L	NA	NA
HPC	5900	col/1ml	92	12
Total Coliform	None Detected	col/100ml	NA	NA

Table 1. Outline of Bacteriological and Parasitic Filtering Capacity of Pilot Units

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serial filtration filtrate were conducted the final week of operation for enterococci, HPC, total coliform and giardia/cryptosporidium. **Table 1** summarizes the bacteriological and parasitic analyses.

Phosphorus, Sulfate and Chlorine Data

Phosphorus, sulfate and chloride analyses were conducted for the pilot facility during the final week of operation. No changes in feed versus filtrate concentrations for chloride or sulfate were observed for the microfiltration unit, which did remove approximately 25 percent of total dissolved phosphorus and about 50 percent of the total phosphorus from the raw influent stream. Little difference was observed between the feed versus the filtrate samples collected, relative to observed concentrations of phosphorus, sulfate, or chloride on the serial filtration unit.

Accumulated Backwash Solids

TCLP analysis on the residual solids indicated there were no detectable concentrations of listed hazardous waste constituents.

Pilot Units Performance Summary

The microfiltration pilot exceeded water-treatment and operational standards established by the project contract requirements in terms of fecal coliform removal and turbidity reduction, and it also demonstrated high operational efficiency. The serial filtration pilot was not reliable in removing fecal coliform or reducing turbidity of the feedwaters. **Table 2** provides a performance summary of both the serial and microfiltration pilot units.

Element	Units	Microfiltration	Serial Filtration
Run Time	Hours	731	624
Approx Gallons of Filtrate	Gallons	420,000	170,000
Total Downtime for Chemical Cleaning / Cartridge Change	Hours	24	1
Nonroutine Downtime	Hours	37	180
Time Backwashing	% of Total Time	10	5
Volume of Backwash	Gallons	88,000	9,000
Solids Production	Lbs / Million gallons filtrate	25	N/A
Total Power Used	kWh	1360	582
Consumption Rate	kWh / Million gallons filtrate	3200	3400
Average Filtrate Turbidity	NTU	0.1	6.3
Sufficient Pathogen Removal?	--	Yes	No
Average Fecal Coliform in Filtrate	Colonies/100mL	None Detected	22
# of Chemical Cleans?	--	3	N/A
Citric Acid Consumption Rate	Lbs / Million Gallons filtrate	57	N/A
Sodium Hypochlorite Consumption Rate	Ounces / Million Gallons filtrate	690	N/A
Operational Efficiency	% of Time Operational	95.5	77

Table 2. Pilot Units Performance Summary

Design Recommendations

Based on recommendations by US Filter, the microfiltration system proposed for the full-scale surface-water treatment facility is a 5-MGD Continuous Microfiltration Submersible (CMFS). Unlike the pressurized CMF unit used in the pilot study, the CMFS is a Cross-Flow with Concentrate Recycle (CFCR) system. This system is quantitatively comparable to the microfiltration pilot unit in terms of hydraulic throughput, membrane specifications, and chemical and electrical consumption.

In the full-scale system, the raw water would first be pumped through a course strainer (400um), then into a header that would distribute the raw water into a train of three filtering cells housing a total of 672 modules (224 membrane modules per cell). Based on the results of the pilot study, the 5-MGD unit would be operated at a flux of 25.8 GFD.

A conceptual flow diagram for a typical full-scale microfiltration unit is shown in **Figure 4**. The units would be installed under a covered roof of 20-foot clearance with open walls on a concrete-slab foundation occupying approximately 4,500 square feet. Backwash and clean-in-place holding tanks would be installed on the concrete slab.

A preliminary conceptual design includes pumping approximately 5.35 MGD to the CMFS treatment plant to produce 5 MGD of filtrate and 0.35 MGD of backwash water. Compressed air at approximately 186 cfm would be delivered to the CMF units for backwashing. Backwash solids and blowdown from the coarse screen would be discharged to an onsite storage basin. Supernatant overflow from the solids storage area would be returned to the MF treatment system for filtration.

Settled solids in the lagoon could be collected and disposed of on adjacent agricultural lands for use as a soil amendment. Alternately these solids could be managed onsite by use of a dedicated land application facility, or they could be dewatered and disposed off site. The backwash water could be pumped into an approximate 0.4-acre lined earthen basin, and the residual solids would be concentrated by gravity settling. Pilot results indicate about 130 pounds of dry solids would be produced each day by a 5-MGD facility drawing surface waters near Lake Okeechobee.

Flux restoration would be accomplished

by cleaning the membranes with a combination of citric acid and chlorine on the average every 30 days. The spent cleaning solutions could be neutralized and discharged onsite into the residual solids lagoon.

A maintenance backwash would occur every 24 hours. This backwash cycle utilizes a low-concentration chlorine solution to routinely remove material accumulated on the membranes (scaling) and provides a degree of daily flux restoration.

Capital Cost Summary

For a 5-MGD CMFS unit, costs for membrane equipment and appurtenances are approximately $1.5 million. Total installed cost for the CMFS and ancillary equipment (coarse strainer, backwash basins, etc.) is $3 million.

Table 3 summarizes the capital costs associated with the 5-MGD CMFS treatment plant. An ASR well system will include a pressurized pumping system, and the cost for these pumps have been included in the estimate provided here. No costs have been estimated for any additional raw-water pumps that may need to be included in a given site-specific design.

Operation and Maintenance Conditions and Costs

Tables 4 and 5 estimate the 5-MGD CMFS operating conditions. Estimates are based on the facility being operational 150 days per year.

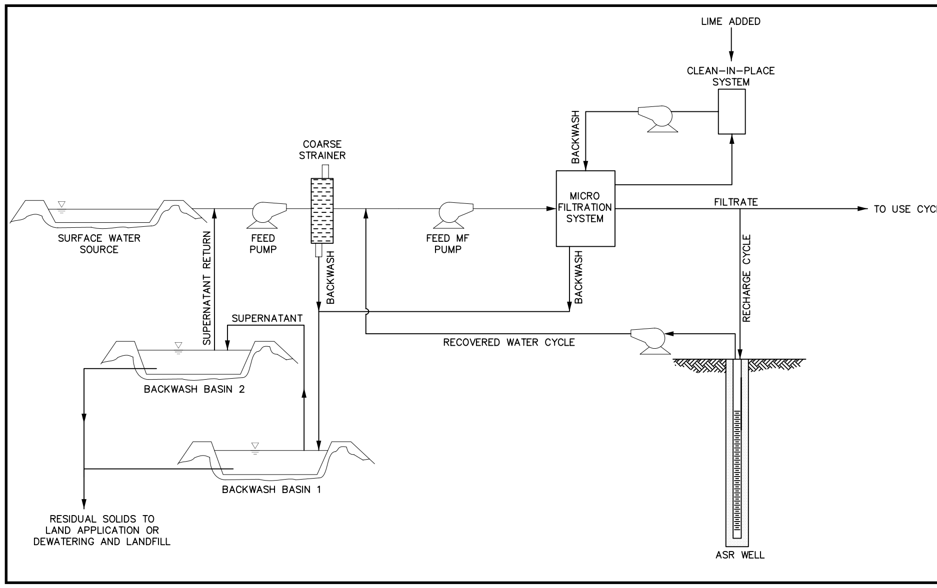

Figure 4. Conceptual Full-Scale 5-MGD Microfiltration Facility for ASR Pretreatment

Item	Estimated Capital Cost ($M)
5-MGD CMFS Equipment	1.5
Plumbing / Excavation	0.10
Coarse strainer system	0.15
Concrete slab and buildings	0.20
Two Backwash Basins	0.15
Sludge dewatering	0.15
Electrical and mechanical installation	0.20
Subtotal	**2.45**
Engineering and contingencies (@30%)	0.55
Total	**3.0**

Table 3. Capital Cost Estimate for 5-MGD CMFS Water Treatment Plant

Plant Data	Value	Units
Daily Filtrate Flow	5,000,000	GPD
Average Daily Feed Flow	5,351,439	GPD
Backwash Interval	22	Min
Maintenance Backwash Interval	24	Hours
CIP Interval	30	Days
Membrane Warranty Period	7	Years
Number of CMF Cells	3	
Number of Modules per Cell	224	
Power Consumption	1038	kWh / day operational
Backwash Volume	339,000	Gallons/Day
Chemical Cleaning Solutions	1500	Gallons/Day

Table 4. Operating Conditions for 5-MGD CMFS Water Treatment Facility

Item	Cost (per year or 750 MG Filtrate)
Membrane Replacement (7-year life)	$52,800
Energy (@ $0.08 kWhr)	$12,500
Operator (2 hours/day @ $40/hour)	$12,000
Maintenance($0.0010/1000gallons)	$800
Chemical	$5,500
Total	**$83,600**

Table 5. Full-Scale Operational Costs