Low cost reclamation using the Advanced Integrated Wastewater Pond Systems® Technology and reverse osmosis


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Abstract The sustainability of wastewater reclamation and reuse schemes is often limited by the increase in salt concentration that occurs with each water use. In this pilot study, we show that the cost of reclaiming wastewater and removing salt can be dramatically decreased by integrating recent advances in wastewater pond design, solids separation equipment, and membrane technology. Effluent from an AIWPS® Facility was clarified in a Krofta® Supracell™ Dissolved Air Flotation (DAF) unit and a Slow Sand Filter (SSF) prior to final treatment in an Expertise S.r.l. reverse osmosis (RO) unit. The ponds of the AIWPS® Facility removed an average of 82% of soluble BOD and 80% of soluble nitrogen. Following clarification, filtration, and RO treatment, the pollutant removals were > 99% for soluble BOD, > 99% for soluble nitrogen, and 98% for TDS. Based on membrane fouling rate data, the cleaning interval for the RO membranes in a full-scale AIWPS®-RO Facility would be over 100 days. This interval is on par with that typically seen in full-scale reclamation facilities treating secondary activated sludge effluent with microfiltration prior to reverse osmosis. A 4-MLD AIWPS®-RO Facility is expected to produce permeate water at substantially lower cost and lower energy consumption (US $698 and 443 kWh per million liters treated) than a system of equal capacity using conventional activated sludge secondary treatment followed by microfiltration and reverse osmosis (US $1274 and 911 kWh per million litres treated). This cost and energy differential is attributable to the lower capital and operating expenses of the AIWPS® Technology in comparison with activated sludge.

Keywords AIWPS® Technology; reverse osmosis; slow sand filtration; dissolved air flotation; suspended solids removal; filtration; water reclamation; wastewater stabilization ponds; algae; activated sludge

Introduction A key element for the sustainability of any multiple-pass water reuse scheme is the removal of the salt increment. The salt increment is the increase in total dissolved solids (TDS) concentration associated with each use; for municipal systems in the United States, the salt increment is typically 150–380 mg/L (Metcalf and Eddy, 1991). If these added salts are not removed prior to reuse, the dissolved solids concentration of the reclaimed water will steadily increase, reducing reuse options. In comparison with conventional mechanical treatment systems such as activated sludge, AIWPS® Facilities are at least 60% less costly to build, operate, and maintain, and two to ten times more energy efficient (Green, 1998). Thus, the overall monetary and energy costs of removing the salt increment via the combined AIWPS®-RO Process should be less than those for reverse osmosis used in conjunction with conventional wastewater treatment.

The chief obstacle to the reclamation of wastewater pond effluent is the removal of total suspended solids (TSS) which are primarily algae. Algal TSS are notoriously difficult to remove from pond effluent (US EPA, 1983). This project demonstrated the feasibility and cost-effectiveness of TSS and TDS removal by the AIWPS®-RO Process. Specifically, we determined that the cost of pretreatment of an AIWPS® Facility’s effluent to the requisite RO feed standards is approximately equal to the RO pretreatment costs for activated sludge.
effluent by microfiltration. By showing that AIWPS® Facility effluent is compatible with membrane reclamation technology, we hope to expand the range of applications for AIWPS® Facilities and other wastewater pond technologies.

Methods

In this pilot study, we used an RO system specifically designed by Expertise Srl for use in conjunction with the AIWPS® Demonstration Facility located at the Environmental Engineering and Health Sciences Laboratory at the University of California, Berkeley. The AIWPS® Facility consists of four components in series: the In-Pond Digesters (IPDs), the Advanced Facultative Pond (AFP), the High Rate Pond (HRP), and the Algal Settling Pond (ASP) (Figure 1). Properties and parameters of the AIWPS® Technology are described elsewhere (Oswald, 1990, Oswald et al., 1994, and Green et al., 1995). Influent to the Facility was domestic sewage from the City of Richmond, California. A grinder pump was used to divert 100 m³/day of sewage through a flow measurement and splitter box and into the IPDs.

The ASP effluent was coagulated and most of the suspended solids were removed with a Krofta® SupraCell™ DAF unit. DAF was selected because of its effectiveness in removing algal suspended solids and its ability to produce an algal float with low water content (Braghetta et al., 1997; Krofta and Wang, 1984, Nurdogan, 1988, Ramani, 1974). The SupraCell™ DAF unit had a volume of 450 L and was operated at 114 L/min for 4 to 5 hours daily. The DAF effluent produced during these runs filled two 15,000-L storage tanks (Figure 1). Flocculation and coagulation in the DAF were enhanced by the use of ferric chloride (FeCl₃), aluminium sulfate (alum), or cationic polymers that are “Generally Recognized as Safe” (GRAS) for animal feed by the U.S. Department of Agriculture. Coagulants were dosed into the 5.1-cm diameter ASP effluent pipe 20 m upstream of the DAF unit, allowing for approximately 20 seconds of mixing. A variety of cationic GRAS polymer flocculants and coagulants were screened as well as a range of alum and ferric chloride coagulant doses. Through this testing, combined with a price comparison of the products tested, we showed that ferric chloride provided the highest level of turbidity and solids removal per unit chemical cost. Ferric chloride was dosed at 44 mg/L as FeCl₃ during the first 730 hours of RO operation and at 66 mg/L thereafter.

Figure 1 Schematic diagram of the AIWPS®-RO pilot facility
The Slow Sand Filters were constructed from two 3.05 m diameter, 2.1 m deep cross-linked polyethylene tanks, filled to a depth of 1 m with media. The base gravel layer was 30 cm of 1.9 to 1.25 cm round gravel topped by a 25 cm layer of pea gravel. These gravel layers covered a network of 7.5 cm diameter corrugated ABS perforated drain pipe. The gravel layers were then covered with a 46 cm layer of 30 mesh, silica, water filter sand. After 180 hours of system operation, layers of geotextile fabric were installed on top of the sand. Research by Graham and Mbwette (1991) suggested that this fabric might increase the interval between filter cleanings. The fabric used was Amoco Style 4512, a nonwoven polypropylene felted geotextile. The fabric was 3.3 mm thick and had a specific surface area of 16,424 m²/m³ and a porosity of 85%. Both sand filters were operated with a covering of between one and seven layers of fabric for the remainder of the test period. The SSFs were operated in parallel at a total flow rate of 19 litres per minute. A constant water depth of 2 m (measured from the bottom of the tank) was maintained in the SSFs. When the combined flow through the filters dropped below 19 litres per minute, operators cleaned the filters. Filter cleaning intervals ranged from five and ten days.

The ultraviolet disinfection unit was an Infilco-Degremont Model 1XS with a design flow of 26.5 litres per minute. At the 19-litre per minute flow used, the minimum dose delivered by the unit was 240 mW/cm² (excluding losses due to water turbidity) which exceeded the minimum 140–160 mW/cm² disinfection dose recommended by the California Department of Health Services (National Water Research Institute, 1993).

The Expertise RO unit included the following pretreatment processes: chlorine disinfection, pH adjustment, coagulation, rapid sand filtration, 50 µm cartridge filtration, 5 µm cartridge filtration, dechlorination, and antiscalant addition. Pretreatment chemicals were added via adjustable metering pumps at the dose points shown in Figure 1. The effectiveness of this pretreatment was measured by the Silt Density Index (SDI) test (ASTM, 2000). Before bringing the RO membranes online, operators performed substantial pretreatment testing to ensure a feedwater SDI of consistently less than 5.0.

The rapid sand filter mounted on the Expertise RO Unit skid consisted of a 650-litre steel tank filled with silica sand and anthracite media. The rapid sand filter was operated with an influent pressure of 3.5 to 4.0 bar and with head losses up to 1.5 bar. The filter was backwashed when the head loss reached 1.5 bar.

The Expertise RO unit was modified to a 11 membrane vessel configuration with three membrane elements in each membrane vessel. The elements were Koch/Fluid Systems 4820HR Spiral Wound Thin Film Composite membranes. The membranes were operated at a feed pressure of 9 to 11 bar. RO membrane fouling rate was calculated from measurements taken by flow and pressure instruments on the RO skid. The water permeation coefficient, A, was calculated using the NORMPRO software provided by Koch/Fluid Systems (1998).

We operated the system for a total of 1500 hours from February through June 1999. During this time, we sampled effluent from each major treatment component in the Facility. The six sample points were: ASP effluent, DAF effluent, UV disinfection unit effluent, rapid sand filter effluent (RSF), concentrate effluent (CONC), and permeate effluent (PERM). The system was monitored several times daily for turbidity and SDI; weekly for total dissolved solids, volatile suspended solids, total suspended solids, biochemical oxygen demand, nitrate nitrogen, ammonia nitrogen, total Kjeldahl nitrogen, alkalinity, soluble reactive phosphorus, total coliform, and *Escherichia coli* (*E. coli*); and bimonthly for calcium, magnesium, iron, manganese, chloride, sodium, potassium, and sulfate. Total organic carbon (TOC) was monitored on three dates in May. In June, operators seeded the reverse osmosis membrane influent with MS-2 bacteriophage, an indicator virus. Indigenous MS-2 bacteriophage concentrations were also measured in the AIWPS®...
Facility influent and in the effluent from the AFP, HRP, ASP, and the DAF unit. Due to space limitations, only a portion of the project results (dissolved and suspended solids, nitrogen, *E. coli* and total coliform bacteria, bacteriophage, and TOC) are presented in the results section, below. The techniques used in the analysis of these parameters are described in *Standard Methods* (APHA, 1995).

We prepared a comparison of the estimated total cost (annualized capital plus O&M costs) and energy use of a generic 4-MLD AIWPS®-RO Facility and a generic 4-MLD activated sludge-microfiltration-reverse osmosis (AS-MF-RO) plant. Costs of primary and secondary treatment in activated sludge and AIWPS® Facilities were taken from Green *et al.* (1996), Green (1998), and Bradley (1993). Land costs were set at US$37,000 per hectare and an annual interest rate of 7% was assumed. Timothy Bowler of the Lenox Institute of Water Technology provided cost and energy consumption information for 4-MLD DAF units. In the 4-MLD AIWPS®-RO Facility, continuous-backwash media filters were substituted for the SSFs used in the pilot study. Continuous-backwash filters have been used successfully for algae removal at full-scale for three years (Maglione, pers. comm.). Parkson Corporation provided operation and cost information on continuous-backwash filters. The Everfilt Corporation provided cost and operations data for pulse-backwash filters similar to the Rapid Sand Filter on the RO skid. The cost and energy requirements for full-scale AS-MF-RO facilities were estimated using a spreadsheet model developed by Dr. Greg Leslie of the Orange County (California) Water District based on experience at Water Factory 21 (Leslie, pers. comm.) and from several papers (Gere, 1997, Morin, 1994, Pickering *et al.*, 1993, Wiesner *et al.*, 1994). We also used the model to estimate full-scale RO costs for the AIWPS®-RO Facility. Use of the model required input data on RO operating pressure, influent and effluent TDS, percent recovery, and membrane replacement interval. These parameters were set equal to the values observed during operation of the AIWPS®-RO pilot unit. The UV disinfection step in the AIWPS®-RO pilot study was not included in the full-scale cost estimate since chlorination costs were included in the spreadsheet model.

**Results and discussion**

*Results below are expressed as mean ± one standard error*

Observed total dissolved solids concentrations remained nearly constant through all stages of the treatment process up to the RO Unit, where TDS concentration decreased from 260±32 mg/L to 5.8±3.8 mg/L (Figure 2). The majority of suspended solids removal occurred...
in the DAF Unit, where TSS concentration decreased from 134±12 mg/L to 21±3.2 mg/L. Through the Slow Sand Filters, TSS concentrations were decreased to 1.6±0.8 mg/L (Figure 3). The same trend held for volatile suspended solids removal; VSS concentration decreased from 114±9.5 mg/L to 15±2.8 mg/L through the DAF Unit, and to 1.7±0.4 mg/L through the SSFs (Figure 3). Based on the nonzero concentration of TSS in the concentrate flow (3.5±1.8 mg/L), some TSS was present in the influent to the RO membranes.

Removal of each species of nitrogen followed a distinct pattern through the treatment system (Figure 4). Organic nitrogen was removed in a pattern similar to that seen for suspended solids removal. The DAF Unit removed 86% of the organic nitrogen, the Rapid Sand Filter removed 0.6±0.1 mg/L, and the RO membranes removed an additional 0.5±0.1 mg/L. Nitrate nitrogen and ammonia nitrogen, by contrast, were not removed by a statistically significant amount (P > 0.10) in the DAF Unit. Nitrate nitrogen increased by 0.8±0.1 mg/L in the Slow Sand Filters, while ammonia nitrogen decreased by 1.6±0.3 mg/L, suggesting nitrification in the filter bed. Ammonia nitrogen and nitrate nitrogen concentrations did not decrease in the Rapid Sand Filter but were decreased to 0.13±0.01 and 0.12±0.03 mg/L by the RO membranes.

The DAF and SSF each were observed to remove approximately 1 log concentration of both total coliform bacteria and *E. coli* (Figure 5). No *E. coli* were detected in the UV disinfection unit effluent, concentrate stream, or permeate stream. The UV unit removed on
average 2 log concentrations of *E. coli* and 3 log concentrations of total coliform bacteria. No coliform bacteria were ever detected in the concentrate or permeate streams. Coliform bacteria were detected twice in the effluent of the UV disinfection unit. The mean coliform concentration in the effluent of the UV disinfection unit was thus 0.8±0.1 per 100 mL (Median values are shown in Figure 5).

In the seeded MS-2 bacteriophage test, the RO membranes reduced mean plaque forming units (PFU) per 100 mL from $7.08 \times 10^5$ to $<1 \times 10^1$ PFU/100 mL ($<10^1$ for all eight samples). Results from the single set of virus measurements performed on the AIWPS® Facility ponds and the DAF unit suggest that virus removal is more rapid than coliform removal (Figure 6).

The DAF was observed to reduce TOC concentration from 66±10 mg/L to 8.7±0.8 mg/L (Figure 7). TOC concentration in the RO feed water was 7.9±1.0 mg/L, compared with 1.2±0.3 mg/L in the permeate.

The RO unit was operated with 75% to 90% system recovery (permeate flow divided by total influent flow) during the experimental period (Figure 8). For the entire experimental period, mean recovery was 83.8%. Excluding the first 150 hours of operation due to wide variations in operational parameters during system startup, a regression line fitted to the water permeation coefficient (A) data had a slope of −0.00037 (Figure 8). According to
Koch/Fluid Systems, the membranes should be cleaned once A declines to 90% of its original value. Extrapolating the regression slope defined by the system’s first 1500 hours of operation suggests that the membranes would not require cleaning until after 2600 hours (108 days) of operation. This cleaning interval is on par with that typically seen in full-scale reverse osmosis plants treating microfiltered activated sludge effluent (Koch/Fluid Systems, 1999). This result is important, as frequent membrane cleaning and replacement is known to increase RO operational costs.

A cost comparison made between a 4-MLD AIWPS®-RO Facility and an AS-MF-RO system indicates that the AIWPS®-RO Facility is 45% less expensive than a conventional plant, with lifetime costs of US$ 698 versus US$ 1274 respectively per million litres treated. The energy consumption observations are similar; the AIWPS®-RO Facility uses 51% less energy than a conventional plant, with energy requirements of 443 kWh versus 911 kWh per million litres treated (Figures 9 and 10).

Breaking down the cost and energy results by each step of the treatment sequence reveals that the combined capital and operational costs for advanced treatment are slightly lower in the AIWPS®-RO Facility than in the AS-MF-RO system (US$ 477 versus US$ 487 per ML treated). Advanced treatment energy requirements for the AIWPS®-RO Facility are somewhat higher than those for the activated sludge system (411 kWh versus 308 kWh per ML treated). The large overall difference in total capital and energy
requirements between the two systems arises from the large capital and energy savings determined for the AIWPS® Technology in primary and secondary treatment (Figures 9 and 10).

Microfiltration is increasingly used for RO pretreatment because it tends to increase the RO membrane cleaning interval (Gagliardo, 1998; Koch/Fluid Systems, 1999) in comparison with media filtration pretreatment. Although media filtration was found to work well in this study, microfiltration should, if feasible, be incorporated into the AIWPS®-RO treatment sequence in future demonstrations.

Conclusions

The successful operation of the AIWPS®-RO Pilot Facility we have described in this study is a demonstration that the AIWPS® Technology is compatible with the highest levels of reclamation technology. Using the AIWPS® Technology in combination with reverse osmosis, one can produce potable-quality effluent at approximately half the cost and less than half the energy consumption of a comparable activated sludge based system. Actual wastewater characteristics, site conditions, and local unit costs will introduce substantial variation in the cost figures presented. Nonetheless, the basic conclusion of this study is likely to hold true across a wide range of circumstances; that is, although the primary and secondary treatment capital and energy costs for AIWPS® Facilities are much lower than those for activated sludge treatment plants, the capital and energy costs for advanced treatment of AIWPS® Facility effluent and activated sludge effluent are likely to be similar.

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References
