

Wastewater reclamation at Lake Arrowhead, California: an overview

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ABSTRACT: A demonstration pilot study was conducted in Lake Arrowhead, Calif., to determine the feasibility of reclaiming municipal secondary effluent for indirect potable reuse and stabilizing the lake level during periods of extended drought. The lake, which is the sole drinking water source for the community, was severely affected during the long drought from 1985 to 1991. A 12 000-L/d pilot plant was constructed and tested for nearly 3 years. The pilot plant included denitrification followed by alum coagulation/flocculation/sedimentation, sand filtration, primary ozonation, granular activated carbon (GAC) filtration, ultrafiltration (UF)/nanofiltration (NF), reverse osmosis (RO), and final ozone disinfection. A comprehensive analytical testing program was devised to monitor product water quality as well as to compare it with the lake water. Phosphorus and turbidity in the product water were consistently below detection limits (0.02 mg/L and 0.1 nephelometric turbidity unit [NTU], respectively). Product water total organic carbon (TOC) and conductivity levels were 1–2 mg/L and 20–40 $\mu\text{Mho/cm}$, respectively, which were approximately 25%–50% and 30%–50% of the lake concentration. Challenge testing revealed nearly complete removal of pathogenic material (an approximate 21–22 log removal of bacteriophage and 8–10 log removal of *Giardia* and *Cryptosporidium*). Trace organic chemical analysis of volatile and base neutral organic compounds indicated that it is possible to produce reclaimed water that is superior to the lake water. Only nitrogen (N) removal did not meet expectations for the entire period. It is anticipated that better process control will ensure meeting the nitrogen product water goals for full-scale treatment. *Water Environ. Res.*, **69**, 350 (1997).

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The drought experienced in Southern California from 1985 to 1991 was one of the longest and most severe, and it is forecast that such extended droughts will continue to occur sporadically. There is an acute need to augment existing drinking water supplies with drought-tolerant resources. Previously, importing water from distant sources was a popular method, but today it is usually expensive or infeasible. Indirect potable reuse from industrial and municipal wastewater discharges after extensive treatment and subsequent natural treatment and storage, such as groundwater recharge, is an attractive alternative. Technical advances in ozonation, carbon adsorption, and membrane separation processes, such as nanofiltration (NF) and reverse osmosis (RO), and monitoring technology make this possible.

The concept of potable water reclamation is not technically new. It requires treating a source wastewater to remove all hazardous contaminants such as dissolved organic compounds, bacteria, viruses, nutrients, and dissolved salts that affect reuse. Several full-scale water reuse plants exist, such as Water Factory 21 (Argo and Montes, 1979; McCarty *et al.*, 1980) in Orange County, California; the Whittier Narrows Groundwater

Recharge Project in Los Angeles County, California (Nellor *et al.*, 1985); the Upper Occoquan Sewage Authority Project in Virginia (Hamann and McEwen, 1991; WPCF, 1989); and the Groundwater Recharge Project in El Paso, Tex. (Asano, 1985; Knorr *et al.*, 1988); however, public and regulatory agencies remain reluctant to accept reclamation technology for indirect potable water reuse. For this reason pilot-scale projects are used to demonstrate technical and economic feasibility; examples include the Aqua III Total Resource Recovery Project in San Diego, Calif. (Western Consortium, 1992), and the Denver Potable Reclamation Demonstration Project in Denver, Colo. (Rogers *et al.*, 1987). These projects are also useful in developing technical databases for regulators, as well as improving water reclamation technologies.

The present project was undertaken to explore indirect potable reuse to provide for additional drinking water supplies in Lake Arrowhead. The community is located in the San Bernardino mountains, 140 km (90 miles) east of Los Angeles in Southern California. Located at an altitude of 1 700 m (5 500 ft) above sea level, the community was developed around Lake Arrowhead, a 3.0-km² (750-ac) recreational reservoir containing up to 5.8×10^7 m³ (47 300 ac-ft) of water. The approximate average depth of the lake is 19 m (62 ft) when it is full. The population of the community was estimated at 10 000 in 1991, but it has a significant seasonal variation reaching up to 17 000 during summer months. Population growth in recent years has averaged about 10% annually, mainly because of conversions from part-time to full-time occupancy and new residential construction. It is expected that the number of water service connections will increase from approximately 6 700, counted in 1991, to 9 000 by the year 2010 (Davidson *et al.*, 1991). Both sanitation and water services are provided by the Lake Arrowhead Community Services District (LACSD). The long drought from 1985 to 1991 coupled with increasing water demand caused a significant drop in the lake level, which reached a historic low in 1992. This diminished the recreational value of the lake but also seriously questioned the long-term sustainability of the lake as the sole drinking water source. The community is not a member of the California Water Project and has no convenience system to the project's terminus. Even if additional surface water were available, such as Colorado River water, the cost of a new supply line and pumping would be prohibitively expensive. The community has no industry or agriculture, which prevents industrial reuse. Because no other alternative was available, wastewater reclamation was proposed to produce additional water needed to stabilize the lake level and ensure water supply during drought years. It was calculated that reclaiming

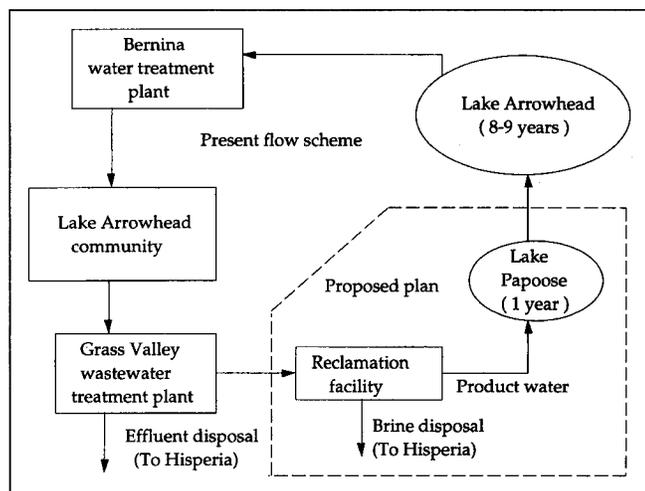


Figure 1—Proposed plan for the Lake Arrowhead reclamation project.

50% of the current wastewater flow would add an equivalent of approximately 0.3 m/a (12 in./yr), more than enough to offset the recent depletions.

The LACSD has two municipal wastewater treatment facilities: the older 3 800-m³/d (1.0-mgd) Willow Creek activated-sludge plant and a new 7 600-m³/day (2.0-mgd) Grass Valley trickling-filter treatment plant constructed in 1990. A major portion of the community's wastewater is treated at the Grass Valley plant. The plant has primary treatment; biological trickling filtration, which achieves biochemical oxygen demand (BOD) removal and nitrification; secondary clarification; and final disinfection with chlorine. The treated effluent is transported through a single pipeline down the mountains to a local town (Hisperia), where it is used for irrigation. The proposed full-scale reclamation facility would most likely be constructed at the Grass Valley plant. The plant is relatively new and was designed to be expanded to meet an anticipated increase in the wastewater flow due to population expansion. The proposed reclamation facility would produce water that would be discharged into Lake Papoose, a small reservoir adjoining Lake Arrowhead, with a volume of 2.5×10^6 m³ (2 000 ac-ft). The water from Lake Papoose can then be allowed to overflow into Lake Arrowhead. The community water supply taken from Lake Arrowhead would close the recycle loop. The existing effluent discharge pipeline could still be used to transport unreclaimed wastewater and brine from the reclamation plant and act as a bypass to the reclamation facility if any major treatment problems occurred. A schematic of this proposed plan is shown in Figure 1.

Presently, there are no regulatory standards in California for surface water discharge when the receiving body of water is a potable source. The Department of Health Services (DOHS) has historically opposed the discharge of treated wastewaters into such sources. Recognizing this, it was decided to demonstrate that a pilot-scale reclamation plant could produce water equal to or better than the quality of water in the lake. It was estimated that Lake Papoose with 1 year of detention time and Lake Arrowhead with 8 years of detention time (assuming 50% reclamation of the present Grass Valley plant flow of 3 800 m³/

Table 1—Summary of key pilot plant objectives.

Compounds	Goal	Unit	Water quality criteria
Inorganic			
TDS	50	mg/L	Lake background level ^a
Nutrients			
Nitrate-N	0.08	mg N/L	Lake background level
Ammonia-N	0.2	mg N/L	Method detection level
TKN	0.2	mg N/L	Method detection level
Ortho-P	0.02	mg P/L	Method detection level
Total-P	0.10	mg P/L	Lake background level
Metals			
Manganese	30	μg/L	Lake background level
Aluminum	40	μg/L	Lake background level
Zinc	270	μg/L	Lake background level
Cadmium	0.5	μg/L	Inland Surface Water ^b
Copper	5	μg/L	Inland Surface Water
Lead	0.9	μg/L	Inland Surface Water
Mercury	0.012	μg/L	Inland Surface Water
Bacteriological			
Total coliform	0	#/100 mL	Total Coliform. Final Rule ^c
Fecal coliform	0	#/100 mL	Total Coliform. Final Rule
Viruses	7	log removal	Groundwater recharge ^d
Organics			
TOC	2 000	μg/L	Groundwater recharge
THM	10	μg/L	Lake background level
Other			
Turbidity	0.2	NTU	U.S. Safe Drinking Water
pH	6.5–8.5	—	U.S. Drinking Water

^a Lake Arrowhead Environmental Monitoring Laboratory, Lake Arrowhead, Calif.

^b SWRCB (1993).

^c Total Coliform. Final Rule (1989).

^d Hultquist et al. (1991).

d) would give adequate time for natural treatment of the reclaimed water equivalent or better than present groundwater recharge projects. A recently constructed water treatment plant at Lake Arrowhead (the Bernina drinking water treatment plant) would be the last barrier between the reclamation facility and the distribution system. The plant employs alum coagulation, adsorption clarification, dual-media filtration, and chlorine disinfection. Even though this proposed project clearly represents indirect reuse with 9 years of detention time available between the point of discharge and the intake to the water treatment plant, it is still expected to be highly controversial within the community. The lake water is of very high quality and is recharged only from snowmelt and rain. Reclaimed water will be required to meet not only the federal and state drinking water standards and the special requirements of the DOHS, but also must not degrade the quality of the lake. After a preliminary review of water quality regulations and from previous reclamation work (Culp *et al.*, 1980; Hultquist *et al.*, 1991; SWRCB, 1993; WPCF, 1989), the most stringent water quality objectives were devised under four scenarios (Table 1):

1. Match the present water quality in Lake Arrowhead to meet antidegradation criteria (SWRCB, 1968). These objectives covered a broad range of contaminants but were especially important for phosphorus and nitrogen.

2. Meet the U.S. Safe Drinking Water Criteria (Safe Drinking Water Act, 1986). These addressed bacteriological and chemical parameters.

3. Meet the Inland Surface Water Plan Criteria (SWRCB, 1993). These were primarily aimed at eliminating toxicity in surface waters, resulting in strict limitations on various compounds, especially heavy metals.

4. Meet the State Reuse Criteria (Hultquist *et al.*, 1991). Because no reuse criteria were available for indirect potable reuse, the proposed groundwater recharge criteria were used.

This paper is an overview of the results obtained during the pilot study. It includes general performance data such as the ability of the individual unit processes in the pilot plant to remove specific contaminants; general water quality data on the product water; and a comparison of the product water with the lake water, treatment objectives, and the community's drinking water (Bernina effluent) quality. The comparisons were made for base neutral organics, metals, pathogens, and disinfection byproducts (DBPs) such as aldehydes and trihalomethanes (THMs). Results of special studies such as microbiological challenge testing, metals removal analysis, and ozone DBPs formation analysis are presented also. It is expected that the findings of this pilot study will be used in the eventual design of the full-scale reclamation facility or facilities for communities having similar needs. This study differs from the other previously cited demonstration projects in that the product water quality goals were higher because of the lake's water quality.

Experimental

Pilot plant description. Secondary effluent from the Grass Valley plant was used as the influent to the pilot plant. The main contaminants of interest included nitrogen (mainly present as nitrate) and phosphorus, organics, total suspended solids (TSS), metals, pathogens, and total dissolved solids (TDS). Processes in the pilot plant included denitrification to remove nitrogen; alum coagulation/flocculation/sedimentation to remove phosphorus, suspended solids, and turbidity; sand filtration to remove residual phosphorus and turbidity; primary oxidation with ozone to disinfect pathogenic material and simultaneously break down refractory organic matter into more biodegradable organic matter; biological carbon filtration for removal or oxidation of the biodegradable organic matter after ozonation; ultrafiltration (UF)/NF as pretreatment for RO to remove TDS and total organic carbon (TOC); and final disinfection with ozone (Figure 2). Two main features of the pilot plant design were the absence of chlorine disinfection altogether and the presence of two membrane filtration steps. Ozone was used instead of chlorine as the primary disinfectant mainly to avoid the formation of chlorine DBPs such as THMs. Ozone was used for its superior oxidation and disinfection capability and its ability to destroy taste- and odor- (T&O-) causing compounds. Accordingly, the existing chlorine contact tanks in the Grass Valley plant were bypassed completely and the secondary clarifier was used as the intake point for the pilot plant. Ultrafiltration or NF was chosen as the pretreatment membrane step for RO to increase the overall plant removal efficiency, but also to protect RO from fouling because of organic material. Another aspect of design was to provide at least two treatment barriers to all contaminants. For example, phosphorus is removed through alum precipitation and RO, while nitrogen is removed through denitrification and RO.

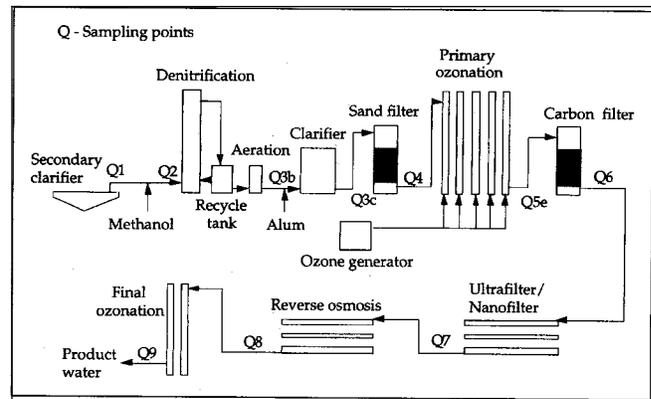


Figure 2—Pilot plant flow scheme.

A tall upflow fluidized-bed denitrification reactor was constructed from a polyvinyl chloride (PVC) column (5.75 m in height and 0.5 m in diameter) and filled with 2.1 m fine sand (0.6 mm) media for supporting biological growth. The retention time in the reactor ranged from 6 to 8 minutes. Methanol was used to provide additional organic carbon for denitrification; the organic carbon in the trickling filter effluent was too refractory for denitrification. A small aeration tank was placed after the denitrification reactor to strip the nitrogen gas bubbles from the denitrified effluent and simultaneously increase the dissolved oxygen (DO) concentration. Provision was also made for a portion of the denitrified effluent to be recycled back into the column. Flow was maintained at 55 litres per minute (LPM) while recycle was varied between 0 and 55 LPM. The expanded media bed depth varied between 2.5 and 4.2 m depending on the total hydraulic flow.

Alum and a high-molecular-weight cationic polymer were used as coagulant and flocculant, respectively, for the clarifier. They were injected directly into the feed, and mixing was achieved with stainless steel in-line static mixers. After comprehensive jar testing, alum and the polymer doses were fixed at 60 and 1.0 mg/L, respectively. Alum was chosen as the coagulant because of its ease of handling; it is also used at the Bernina treatment plant. The retention time in the sedimentation tank was approximately 6 hours for a feed flow of 45 LPM. The clarified effluent was further filtered in a pressurized sand filter, which used fine sand (0.6 mm) as the media. The media depth was 1.2 m, and there was an additional headspace of 1.2 m; this allowed for 100% expansion during filter backwashes. Flow to the filter was maintained at 35 LPM, and the filter was automatically backwashed every 6 hours.

Primary ozone oxidation was achieved in five PVC columns (0.3 m in diameter and 6.0 m high). Oxidation with ozone was intended for two purposes: to achieve the disinfection of pathogenic material and to break down high-molecular-weight refractory organic compounds into smaller more biodegradable compounds, which could be metabolized during biological carbon filtration. The ozone columns were operated in a counter-current mode. The liquid was pumped into the columns near the top, and the ozone gas was fed through the base of the columns. Fine-pore ceramic dome diffusers were used to enhance ozone gas transfer. An antisiphon loop was constructed after the fifth column to ensure a standing column of water in all the columns. An electric spark generator was used to produce

ozone from pure oxygen. Inlet gas-phase concentrations ranged from 0.5% to 1% of ozone by weight. The retention time in the columns ranged from 20 to 40 minutes depending on feed flow. The ozone dose varied from 10 to 20 mg/L depending on ozone concentration in the feed gas. The ozonated effluent was filtered through a granular activated carbon (GAC) filter. The GAC filter was similar in design to the sand filter and was filled with approximately 1.2 m of Filtrasorb F-400 GAC (Calgon Corp., Pittsburg, Pa.); in addition, there was 1.2 m of headspace for 100% bed expansion during backwashes. Flow to the filter was maintained at 20 LPM, and the filter was automatically backwashed every 8 hours. The filter was operated in a biological mode to avoid the costs of regenerating or replacing spent media. The filter feed was saturated with DO after oxygen absorption in the ozone columns, and this provided adequate DO for biological growth with an oxygen residual after GAC filtration.

The effluent from the GAC filter was collected and pumped through the first membrane filtration unit (Figure 3). Table 2 is a description of the main features of the three membranes used in this study. Spiral-wound membranes were used instead of hollow-fiber membranes because of the presence of solids and organics in the feed water and their potential to foul the membrane surface. Fouling affects the performance of the membranes by decreasing the product water throughput and quality. Thin film membranes were used instead of the conventional cellulose acetate membranes; they were expected to run at high permeate recoveries (60%–80%) and low operating pressures (100–200 psi). Provision was made for both acid and antiscalant to be injected into the feed. The entire unit was designed for a total product water flow of 6 to 12 LPM depending on ambient conditions and the quality of the feed water. The product water from the RO unit was pumped through two PVC columns (0.15 m in diameter and 6.1 m high) for final disinfection with ozone. The feed ozone gas was drawn from the same generator that fed gas to the primary ozone columns.

It should be noted that there is a substantial decrease in the design flow between the first and the last unit processes. This was done deliberately to avoid flow control problems in the individual units. All valves were either manually operated ball valves or manually operated needle valves, and it was easier to operate the plant continuously when the feed tanks were either full or had constant overflow. This mode of operation would not be used in a full-scale facility. The plant was operated at steady state, which would also be used in a full-scale facility, because only a constant fraction of the total wastewater flow would be recovered.

Analytical protocol. The key sampling points for individual unit processes are numbered Q1 through Q9 in Figure 2. Field parameters such as pH, turbidity, temperature, alkalinity, DO, and hardness were measured three times a week on grab samples taken directly from sampling ports located on process effluent lines. Sampling was performed on all unit processes, and measurements were performed on site immediately after sampling. Alkalinity and hardness were measured using the standard titrimetric method, while pH, temperature, and DO were measured using probes. Turbidity was measured using a Hach Model 2100A turbidimeter. The same grab samples were later analyzed using a Dionex ion chromatograph (IC) at the University of California, Los Angeles (UCLA), to identify and quantify monovalent and divalent anions such as sulfate, phosphate, nitrate, nitrite, fluoride, and chloride (U.S. EPA, 1984). After December

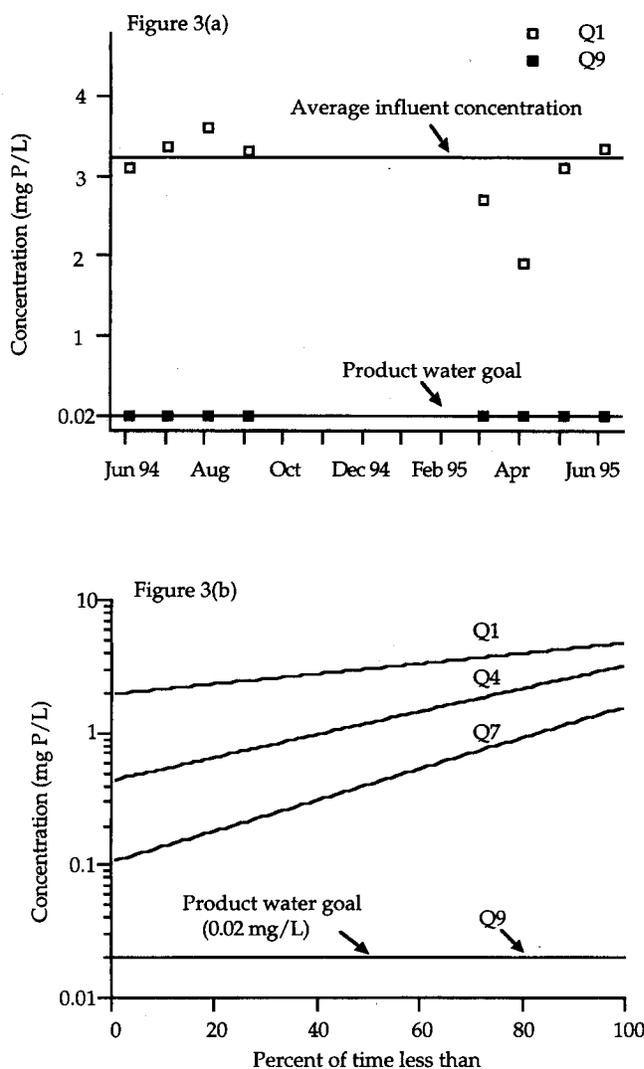


Figure 3—Phosphorus removal for 1994-1995: (a) monthly average influent and product water concentrations; (b) log-linear data distribution fits for key sampling points (product water was below detection limit during entire testing period).

1994, additional nitrate measurements were made using a nitrate probe. Ammonia and organic nitrogen (TKN, total Kjeldahl nitrogen) were measured weekly using the probe method and the standard Kjeldahl method. The TKN measurements were discontinued after September 1994. Both field and IC analysis were performed three times a week during a regular data collection phase from June 1994 to December 1994, but toward the end of the test program from April 1995 to June 1995, grab samples were collected three times a week and composited before analysis. Metals were analyzed for 4 consecutive weeks in June 1995 using inductively coupled plasma emission spectroscopy and mass spectrometry (ICP-MS).

Total organic carbon measurements were made on a Dohrman DC-80 carbon analyzer. The UV absorption at 254-nm measurements were made on a 5652 Hewlett Packard diode array spectrophotometer. Measurements during regular data collection were

Table 2—Membranes installed in the ultrafilter, nanofilter, and reverse osmosis units.

Item	Ultrafilter	Nanofilter ^a	Reverse osmosis ^b
Membrane element size ^c			
Model	G 10	DK 4040	SG/AG 4040
Diameter	4 in.	4 in.	4 in.
Length	40 in.	40 in.	40 in.
Number of elements	3	6	3
Configuration	Spiral-wound	Spiral-wound	Spiral-wound
Material	Thin film	Thin film	Thin film
Mol. weight cutoff	2 500	200	—
Performance/rejection (% removal)			
Organics Fructose	—	98	—
Humics	—	—	—
TDS	—	—	98.7/99.0
Mg ²⁺	—	—	99.5
SO ₄ ²⁻	—	98	99.5
Na ⁺	—	—	98/99.0
Cl ⁻	—	50	98.8/99.0
Operating pressure (psi)	75–200	150–250	100–400

^a NF tested under 100 psi, 1 000 mg/L salt, and 2% fructose.

^b RO tested under 200 psi and 528 mg/L TDS.

^c Membrane elements purchased from DESAL Inc., San Diego, Calif.

made on grab samples collected from all the sampling points, but toward the end of the program the samples were composited every week before analysis. Biodegradable dissolved organic carbon (BDOC) analysis was conducted once a week. This procedure quantified the portion of the dissolved organic carbon (DOC) that was biodegradable (Servais *et al.*, 1989). The samples were inoculated with seed microorganisms, and the change in DOC after a 28-day incubation period was reported as BDOC. The time period of 28 days was chosen on the basis of laboratory evaluation. Because the carbon filter was operated in a biological mode, this analysis was useful in assessing the filter removal efficiency. The analytical protocol for BDOC is described in detail by Khan *et al.* (1996).

Base neutral organic analysis was performed using a Finnigan 4000 automated gas chromatograph and mass spectrometer (GC-MS). The analysis was performed on the extracts from different unit operations, the product water, the lake water, and the drinking water treatment plant effluent to identify and quantify semivolatile, nonpolar organic compounds using an automated form of extraction based on EPA Method 625 (Longbottom and Lichtenberg, 1982). The extractions were performed at the pilot plant and the analysis was performed at UCLA. In general, 10–80 L of the water sample was extracted with methylene chloride, in a 2-L/hr continuous liquid-liquid extractor (CLLE) (Baker *et al.*, 1987), and concentrated to 1 mL for subsequent analysis. With the CLLE, it was possible to identify and quantify the concentrations of contaminants at parts per trillion level instead of parts per billion level. In addition, volatile organic compounds (VOCs) were analyzed according to the EPA 502.2 procedure employing Purge and Trap, and subsequent GC measurement with a Hall detector. The VOC measurements were limited to product water, lake water, and Bernina effluent samples. Aldehyde samples were derivatized with *o*-(2,3,4,5,6-pentafluorobenzyl)-hydroxylamine (PFBHA) and analyzed using a GC with electron capture detection (ECD) (Scli-

menti *et al.* 1990). This procedure quantified formaldehyde, acetaldehyde, propanal, butanal, decanal, and glyoxal.

Coliform testing was performed routinely (weekly or bi-monthly) on site using the multiple test tube technique for calculating the most probable number (MPN). Testing was mostly limited to product water samples. Presence/absence indicator tests were also performed on the same samples. Challenge studies were undertaken once during the course of the test program to assess the removal capability of key treatment processes; this included bacteriophage testing on primary and final ozone columns and UF/NF/RO processes, and *Giardia* and *Cryptosporidium* testing on UF/NF/RO units.

Chronology of pilot plant operation. The construction of the plant began in July 1992; during this phase, data were collected on the primary phosphorus and nitrogen removal units. Initially, an upflow direct filter (adsorption clarifier) was tested for a period of about 6 months to achieve simultaneous phosphorus and turbidity removal. Alum and various high-molecular-weight polymers were tested to affect removal; however, because of the relatively high volume of sludge production from alum precipitation, filter head losses accumulated rapidly. This required backwashing the filter at intervals of approximately 15 to 30 minutes. In addition, the precipitating flocs were breaking continually through the filter bed, increasing effluent turbidity and phosphorus concentrations. To improve performance, a conventional clarifier consisting of separate flocculation and sedimentation tanks was assembled and placed on line in August 1993.

Also, the denitrification reactor was evaluated during this initial start-up period. During the initial months, the biological growth on the sand media was slow, and to accelerate growth, biosolids from the Willow Creek activated-sludge plant were periodically mixed with the contents of the recycle tank. Initially, the nitrogen bubbles that formed during denitrification affected the performance of the sedimentation tank. The nitro-

gen bubbles were being trapped within the precipitating flocs, and this decreased the floc settleability. To counter the problem, an aeration tank, with a holding time of 4 minutes, was placed after the denitrification reactor, and the denitrified effluent was stripped continuously of nitrogen bubbles. Aerating the denitrified effluent also increased its DO concentration and prevented anaerobic or anoxic conditions in the sedimentation tank.

Tests were conducted also during this period on the primary ozone columns and the biological carbon filter. This included establishing the BDOC analysis procedure, conducting preliminary UV absorption experiments to optimize the primary ozone columns. Also, experiments were conducted to assess ozone mass transfer efficiencies and ozone transfer rates; this included setting up a gas- and liquid-phase measurement apparatus. During the initial phases of the project, there were numerous mechanical problems with the NF/RO processes. The manufacturer's design did not include sufficient vibration control for the positive displacement pumps. Check valves within the pumps broke, and piping connections continuously loosened and leaked. The pump mounting assembly was reengineered to minimize vibration and the pumps were rebuilt. In addition, all low-pressure PVC piping connections were replaced with stainless steel fittings, and PVC pipes were replaced with flexible stainless steel hoses, capable of withstanding high pressures and intense vibrations from the pumps. The unit was tested for stable operation for a month prior to intense water quality data collection.

The entire plant was placed on line in June 1994, and intense data collection proceeded through October 1994. In November 1994, the original NF membranes were replaced with new NF membranes, and the RO membranes were replaced with tighter membranes to enhance nitrogen removal. In addition, a new UF unit was constructed and installed in parallel to the NF unit. The plant was operated until the end of 1994 and shut down briefly during the winter months. Data collection resumed in March 1995 and proceeded until June 1995, during which period special studies including challenge testing, metals removal analysis, and ozone DBP formation analysis were undertaken.

Results and Discussion

Basic water quality. The important contaminants of interest in the secondary effluent were the nutrients phosphorus and nitrogen. It was necessary to remove phosphorus and nitrogen to prevent potential eutrophication in the lake.

Phosphorus. Phosphorus was mainly present as orthophosphate (PO_4^{3-}) in the secondary effluent and averaged 3.2 mg/L. The alum clarifier and the sand filter were operated to remove 60%–75% of the influent phosphorus. Though it was possible to remove more than 90% of incoming phosphorus through precipitation, the clarifier and filter were operated deliberately at lower removal efficiencies to decrease sludge production. Subsequent NF and RO units were used to remove the remaining phosphorus. Figure 3 shows the removal efficiency of the pilot plant for a period of 1 year. The data are illustrated in two different ways: (1) the monthly average values of secondary effluent and pilot plant product water are plotted in Figure 3a, and (2) the log-linear probability distributions of the effluent concentrations from each of the key unit processes are given in Figure 3b. Curves Q1, Q4, Q7, and Q9 represent the exponential fits used to represent concentration data of secondary effluent, sand filter effluent, NF effluent, and product water, respectively. It was observed that

exponential fits were better than linear fits in representing the data; however, curve Q9, which represents product water concentration data, is horizontal because the concentration was consistently below the method detection limit of 0.02 mg/L. In addition, total phosphorus was measured also using ICP emission spectroscopy, when metals testing was performed. Total phosphorus concentration in the product water was always below that of the set objective of 0.1 mg P/L (Table 3).

Nitrogen. The trickling filters present in the Grass Valley plant completely nitrified the ammonia present in the raw wastewater entering the plant; thus, nitrogen in the secondary clarifier effluent was present mainly as nitrate. The concentrations of nitrate-nitrogen in the secondary effluent averaged 10.6 mg/L. Because considerable nitrate removal occurred only in the denitrification and RO processes, the monthly average values of secondary effluent (Q1), denitrification reactor effluent (Q3b), and product water (Q9) are plotted along with average ambient water temperature (Figure 4a). In addition, the log-linear distributions of data for key sampling points are plotted, as in the case of phosphorus (Figure 4b).

To meet the target effluent nitrate-nitrogen concentration of 0.1 mg/L, an overall removal efficiency of 99% was required. It was calculated that this goal could be achieved by 90% removal through the denitrification and the membrane separation processes. A target nitrate-nitrogen concentration of 1.0 mg/L was therefore set as the objective for the denitrification process. It was concluded after the initial testing phase that the denitrification reactor would be successful in removing up to 90% of the incoming nitrate provided that methanol were injected in excess of the stoichiometric dose of 35 mg/L (approximately 45 mg/L). The denitrification column was operated successfully in this mode during 1992–1993 (Madireddi *et al.*, 1994). However, the excess methanol resulted in higher TOC concentrations in the denitrified effluent. After the intense data collection began on the entire pilot plant, it was noted that the unused methanol present in the denitrified effluent was not efficiently removed by the membrane processes and resulted in unacceptable TOC concentrations in the final product water. The problem was even more serious during periods of low nitrogen loading to the Grass Valley plant.

To counter this problem, the methanol dose to the denitrification reactor was decreased to 30 mg/L, which was slightly below the stoichiometric need, during the first month of intense data collection. This consequently decreased the denitrification reactor efficiency and the overall nitrate removal. In addition, as nitrate-nitrogen concentration in the pilot plant influent varied significantly (10.6 ± 3.8 mg/L), it was difficult to maintain consistent denitrification with constant methanol dose. For this reason, the effluent nitrate concentrations met the process objective only 30% of the time. Two different RO membranes were tested to increase nitrate removal: the older DESAL SG 4040 membranes, which were rated for 80% nitrate removal, and the newer DESAL AG 4040 membranes, which were rated for 90% nitrate removal. However, this removal efficiency by itself was not sufficient to meet the product water goal during the study.

Nitrate removal can be improved in a full-scale plant by increasing the retention time in the denitrification reactor. The hydraulic retention time in the reactor used in this study was 6 to 8 minutes. A larger denitrification reactor could be used to allow for endogenous denitrification to take place, which requires little or no organic carbon addition. It is estimated that

Table 3—Contaminant concentrations in the Grass Valley plant secondary effluent and pilot plant product water for 1994–1995.

Parameter ^a	Number of samples	Secondary effluent	Product water	MDL ^b	Estimated goal
Nutrients					
Nitrate (NO ₃ -N)	85	10.6 ± 3.8	1.0 ± 1.2	0.01	0.1
Nitrite (NO ₂ -N)	55	0.2 ± 0.3	<MDL	0.01	0.1
Ammonia (as N)	30	1.1 ± 1.6	<MDL	0.2	MDL
Organic-N (TKN)	10	2.6 ± 0.7	<MDL	0.2	MDL
Ortho-P	55	3.2 ± 0.8	<MDL	0.02	0.02
Total-P (ICP)	5	2.9 ± 0.4	0.05 ± 0.02	0.05	0.1
Conventional					
pH	105	7.5 ± 0.4	6.3 ± 0.3	—	6.5–8.5
Alkalinity	75	78 ± 16	7.0 ± 3.0	—	—
Hardness	75	90 ± 13	5.0 ± 2.0	—	—
Dissolved oxygen	55	7.0 ± 2.0	>15	—	—
Temperature, °C	105	17 ± 9	17 ± 9	—	—
Turbidity, NTU	105	6.3 ± 2.8	<MDL	0.1	0.2
TSS	75	12 ± 6.8	<MDL	0.2	0
Bacteriological					
Total coliform, per 100 mL	30	1.1 × 10 ⁶	<2.2	—	<2.2
<i>E. coli</i> (fecal), per 100 mL	30	—	<2.2	—	<2.2
Streptococcus, per 100 mL	15	—	<2.2	—	<2.2
Inorganic					
Conductivity, μMho/cm	105	350 ± 90	30 ± 20	10	80
Sulfate	70	32 ± 19	0.8 ± 0.7	0.03	1.0–3.0
Chloride	70	46 ± 13	9.6 ± 3.8	0.02	10–15
Fluoride	55	0.30 ± 0.05	0.05 ± 0.01	0.015	0.1
Calcium	5	24.2 ± 1.7	0.04 ± 0.02	0.005	15
Magnesium	5	4.4 ± 0.35	0.01 ± 0.008	0.001	2.0
Sodium	5	44 ± 2.1	2.2 ± 0.56	0.030	10
Potassium	5	2.9 ± 0.38	<MDL	0.130	2.0
Organic					
TOC	85	13.0 ± 2.80	0.85 ± 0.62	0.05	2.0
UV absorption units at 254 nm	90	0.197 ± 0.052	<MDL	0.002	—

Values are calculated for the entire test period (combined NF and UF readings).

^a Units in mg/L unless otherwise specified.

^b Method detection limit.

doubling the retention time would achieve the nitrate-nitrogen goal of 1.0 mg/L with stoichiometric methanol doses. In addition, process controllers could be used to control the flow of methanol depending on the nitrate concentrations in the secondary effluent. These procedures were not undertaken during the pilot study but should be included and tested in full-scale design without significantly adding to capital costs. The other forms of nitrogen present in the secondary effluent were ammonia, nitrite, and biological nitrogen (TKN). These were present only in trace concentrations and as such were removed during membrane filtration (Table 3).

Conventional. Turbidity, TSS, and TDS were also closely monitored. Because of the presence of the clarifier, the sand filter, the biological carbon filter, and the two membrane processes (NF/RO or UF/RO), the removal of these constituents was always well in excess of the set objectives. Turbidity measurements were performed on all process effluents. The turbidity of the product water and membrane effluent samples (UF, NF, and RO) were consistently below the product water goal of 0.2 NTU. The TSS measurements were also routinely performed on samples from Q1 to Q6; measurements on membrane effluent

and product water samples were discontinued because TSS could not be detected in these samples. Conventional TDS analysis (according to standard methods) was not performed, but conductivity measurements were taken for all samples, and these values were used to represent TDS. It was found that the product water conductivity was consistently below the lake concentration. The removal efficiency with respect to turbidity and conductivity is illustrated in Figures 5a and b and Figures 6a and b, respectively.

TOC. In general, it was observed that TOC removal efficiency was high and consistent when NF was operated in series with RO. The product water concentrations were below the goal of 2.0 mg/L for the first 6 months of the testing phase from July 1994 to December 1994 (Figure 7a). The tighter RO membranes, which replaced the older membranes in November 1994, were only marginally superior in removing TOC. The overall TOC removal efficiency was lower from March 1995 to May 1995, when UF was operated in series with RO. This was because a major portion of TOC in the membrane feed water consisted of low-molecular-weight compounds formed during primary ozone oxidation, and because UF membranes have a

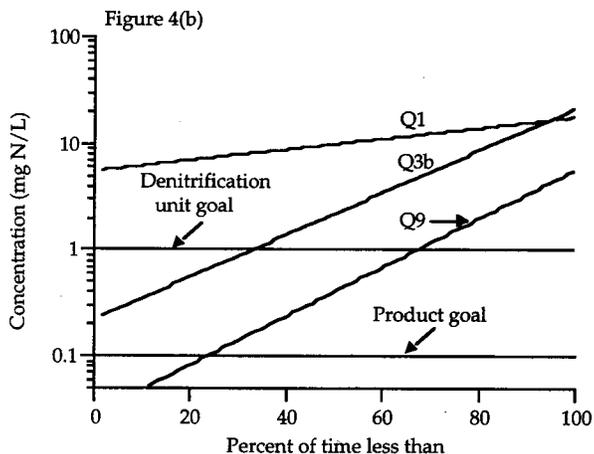
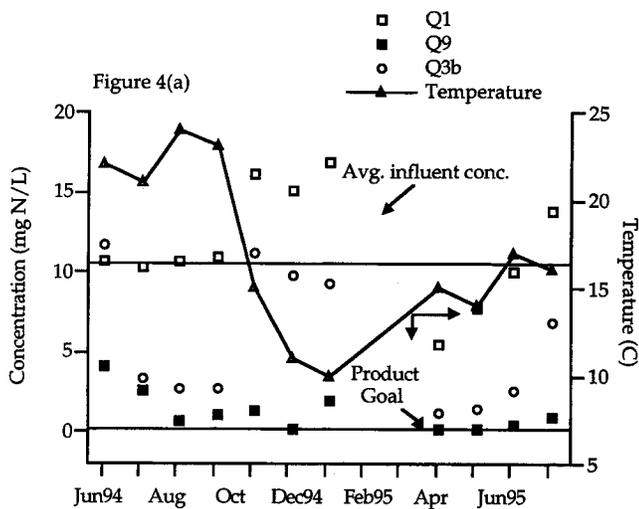


Figure 4—Nitrate removal for 1994-1995: (a) monthly average influent, denitrified effluent, and product water concentrations and ambient water temperature; (b) log-linear data distribution fits for key sampling points.

relatively high-molecular-weight cutoff (2 500 daltons in this case), these compounds leaked across the membrane processes. Because of this difference in the quality of performance of NF and UF units, the TOC data distribution has been plotted separately for each of these membranes in Figure 7b; the UF permeate and the associated product water concentrations are shown as dotted lines.

The performance of the primary ozonation and biological carbon filtration as a single treatment step depended on the ability of ozone to oxidize refractory organics present in the influent into BDOC, and the ability of the carbon filter to remove the BDOC that is formed as a result of ozonation. Ultraviolet absorption at 254 nm was used as an approximate indicator of the extent of cleaving of moderate and high molecular double-bond organic compounds. It was expected that a portion of the products formed from such cleaving would contribute to BDOC. The data collected during the entire test period indicate that there was an approximate decrease of 35% in UV absorption

across the primary ozone columns (0.145 ± 0.034 absorbance units [au] to 0.098 ± 0.032 au). The value further decreased to 0.075 ± 0.024 au after carbon filtration, indicating some concurrent removal of refractory organics as well. No UV absorption (at 254 nm) was detected in the RO permeate and the product water, indicating a minimal presence of refractory organic matter that can absorb UV light.

The BDOC data indicate that there was considerable formation of BDOC during primary ozonation. The concentration values increased from 1.67 ± 0.67 mg/L present in the influent to the primary ozone columns (Q4) to 2.56 ± 0.86 mg/L present in the effluent (Q5e), which is an increase of approximately 55%. The carbon filter was successful in removing a portion of this BDOC; the BDOC in the carbon effluent was 1.18 ± 0.46 mg/L, indicating 55% removal. The samples from Q7 that were NF or UF treated also were measured for BDOC for comparison. No BDOC was detected in the NF permeate, while BDOC concentration in UF permeate was 0.89 ± 0.49 mg/L. This can be attributed to the higher pore size cutoff of the UF membrane

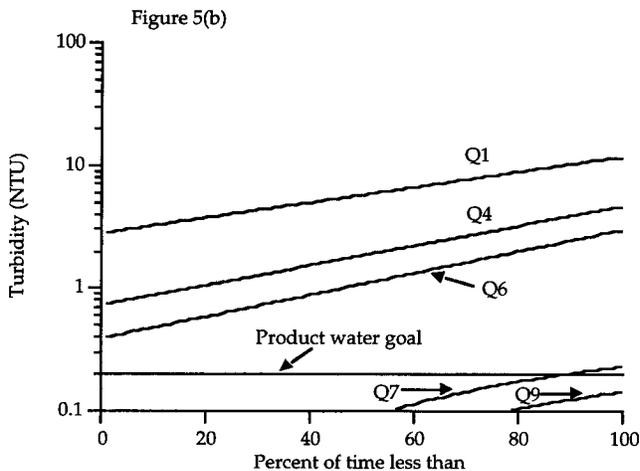
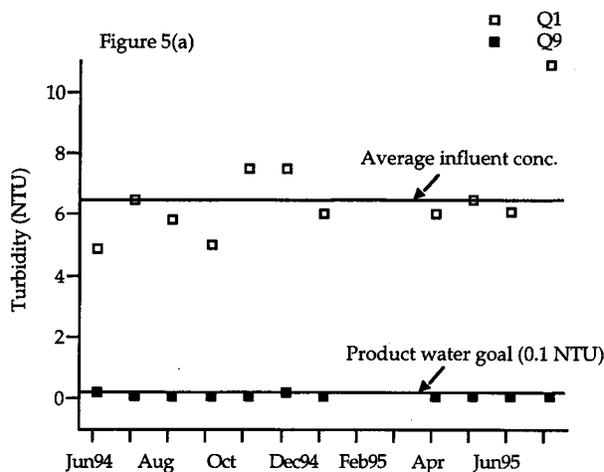


Figure 5—Turbidity removal for 1994-1995: (a) monthly average influent and product water turbidity; (b) log-linear distribution fits for key sampling points.

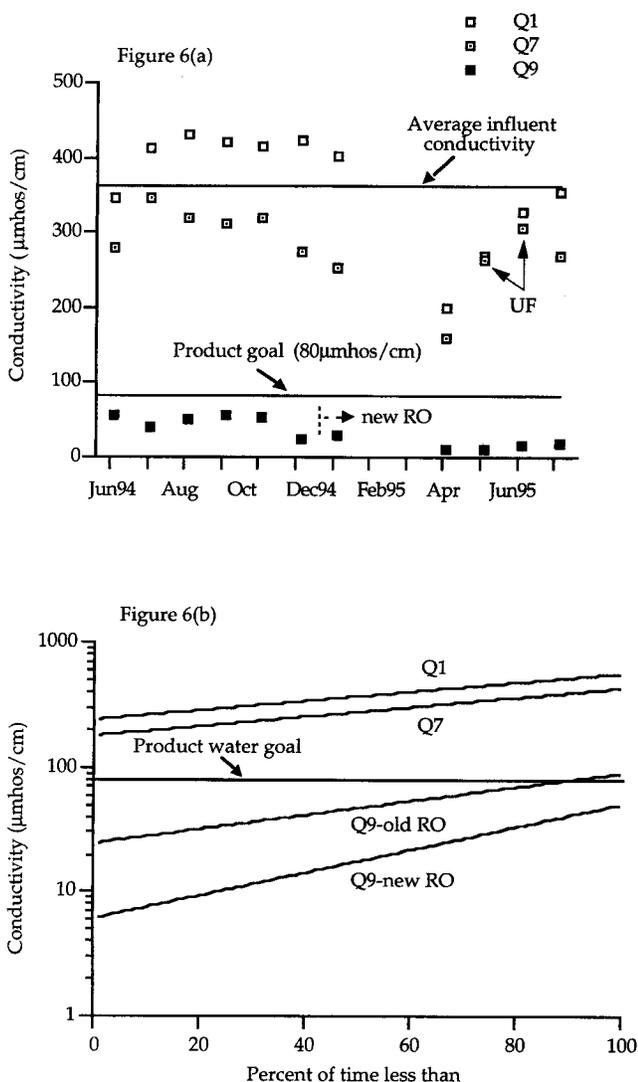


Figure 6—Conductivity removal for 1994-1995: (a) monthly average influent, UF and NF permeate, and product water concentrations (data marked UF represents ultrafiltration and reverse osmosis runs); (b) log-linear data distribution fits for key sampling points (data collected from old and new reverse osmosis membranes are plotted separately).

(2 500 molecular weight). The UF and NF permeate data are further discussed in the section on special studies.

Bacteriological. Bacteriological testing performed on site revealed the removal of *E. coli* and *Streptococcus* bacteria to below detection limits. Both UF and NF were effective in removing coliforms. Only occasionally (four times during the entire study), it was observed that coliforms were detected in the membrane effluent samples (<5/100 mL). This was attributed to bacterial growth in the membrane effluent pipes. However, these residual coliforms were removed completely during final ozonation.

A summary of the overall water quality analysis is given in Table 3. It includes average values of the secondary effluent, the product water, and the established product water goal, along with an approximate number of the samples that were collected

during the test program. The method detection limits of the instruments that were used are also given where they are relevant. The values given in this table only reflect the overall removal efficiency of the pilot plant; individual differences of each phase of operation such as the operation of UF or NF, or the effect of replacing the loose RO membranes with tighter RO membranes, have been ignored to conserve presentation.

Special studies. A series of special studies were performed to quantify various aspects of plant performance. These studies were conducted at specific times during pilot-scale testing for limited periods of up to 4 weeks.

Base neutral organic analysis. The results of the GC-MS analysis revealed the presence of EPA-625 target compounds, such as low-molecular-weight phthalates, in the extracts of the lake water, the drinking water, and the pilot plant product water samples (Table 4); however, these compounds were removed by the pilot plant to concentrations less than normally found in

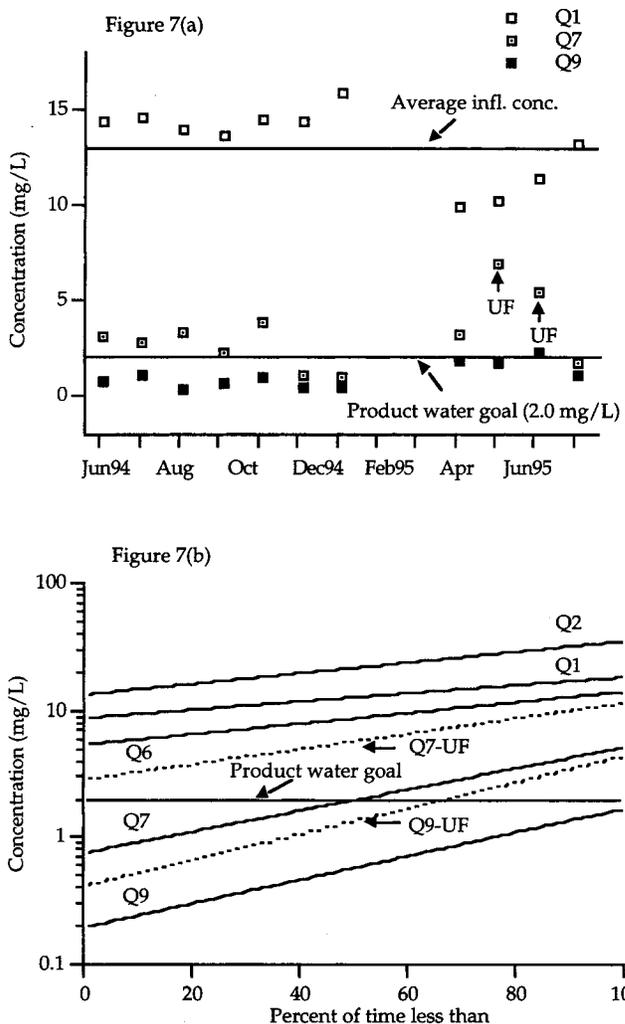


Figure 7—TOC removal for 1994-1995: (a) monthly average influent, UF and NF permeate, and product water concentrations (data marked UF represents ultrafiltration and reverse osmosis runs); (b) log-linear data distribution fits for key sampling points (dotted lines represent data collected when UF was operated).

Table 4—Base neutral and VOC analysis.

Compound	MDL ^a	Product water	Lake water	Drinking water
Base neutral compounds	µg/L	ng/L^b	ng/L	ng/L
Benzoic acid	0.5	<MDL	5.29	36.5
2,4,5-trichlorophenol	2.10	<MDL	<MDL	10.7
1,4-dichlorobenzene	0.084	<MDL	4.53	<MDL
Hexachloroethane	0.167	<MDL	<MDL	5.07
Nitrobenzene	0.66	<MDL	1.42	<MDL
Naphthalene	0.068	<MDL	<MDL	0.96
2-methyl naphthalene	0.125	<MDL	<MDL	0.37
Hexachlorocyclopentadiene	2.43	<MDL	<MDL	6.50
Dimethyl phthalate	0.064	<MDL	<MDL	8.61
Diethyl phthalate	0.060	<MDL	2.46	16.9
Azobenzene	0.063	<MDL	<MDL	0.64
Phenanthrene	0.064	<MDL	<MDL	0.61
Anthracene	0.070	<MDL	<MDL	0.57
Di-n-butyl phthalate	0.060	25.6	366	696
Butylbenzyl phthalate	0.30	<MDL	51.6	6.03
Bis (2-ethylhexyl) phthalate	0.048	0.65	33.7	130
Di-n-octyl phthalate	0.064	<MDL	0.96	0.76
Volatile—EPA method 502.2	µg/L	µg/L	µg/L	µg/L
Chloroform	0.2	0.79	<MDL	9.05
Bromodichloromethane	0.2	0.7	<MDL	2.93
Dibromochloromethane	0.2	0.5	<MDL	0.33

Note—All samples for base neutral analysis were concentrated by a factor of approximately 76 000.

^a Method detection limits based on 1.0-L samples.

^b Nanograms/litre.

the drinking water and lake water. Phthalates are generally used in the production of plastics and resins and are detected in all waters that have been contacted by things such as plastic caps, pipes, food-packaging materials, and others. The compounds detected in the product water at levels indicated in Table 4 are less than drinking water standards. The values reported are presented for comparison, without correction for analytical recovery. A detailed analysis of the GC-MS analysis data along with other aspects of organic carbon removal, especially in the biological carbon filter, will be presented in a future paper.

VOCs. VOC analysis performed, according to the EPA procedure 502.2, on the lake water, the drinking water, and the pilot plant product water samples are also tabulated (Table 4). As expected, no compounds were detected in the lake, which is a water source that is not contaminated by chlorine-treated waters. However, THMs were detected in the drinking water and the pilot plant product water samples. The drinking water sample had a considerably higher total THM level (12 µg/L) than the pilot plant product water (2 µg/L). This was expected because the drinking water treatment plant used chlorine treatment for disinfection. The THMs detected in the product water originate in the raw wastewater coming into the Grass Valley plant. However, the total THM concentration was well below the federal drinking water standard of 100 µg/L and also lower than the potential of the lake water to form these compounds (as observed in the drinking water treatment plant).

Ozone DBP analysis. The analytical method for ozone by-products detected formaldehyde, acetaldehyde, propanal, butanal, decanal, and glyoxal. Analyses were performed periodically from August 1994 to June 1995. Product water concentrations

are plotted as a function of time (Figure 8a), and the general formation and removal through each of the pilot plant processes is shown in Figure 8b. The main compounds that were detected were formaldehyde, acetaldehyde, and glyoxal; formaldehyde formation was primarily attributed to the presence of residual methanol in the water via denitrification, while acetaldehyde and glyoxal were considered to be the byproducts formed from the breakdown of natural organic matter (NOM). The total aldehyde concentration in the product water was less than 10 µg/L. Aldehydes were detected also in the lake and the drinking water treatment plant samples at approximately similar concentrations (see Table 6). However, the concentrations found in both these samples do not reflect their true aldehyde formation potential. Both the lake water and the drinking water samples were not ozonated, and the presence of NOM in these waters considerably increases their aldehyde formation potential. Thus, the total aldehyde formation potential of the lake

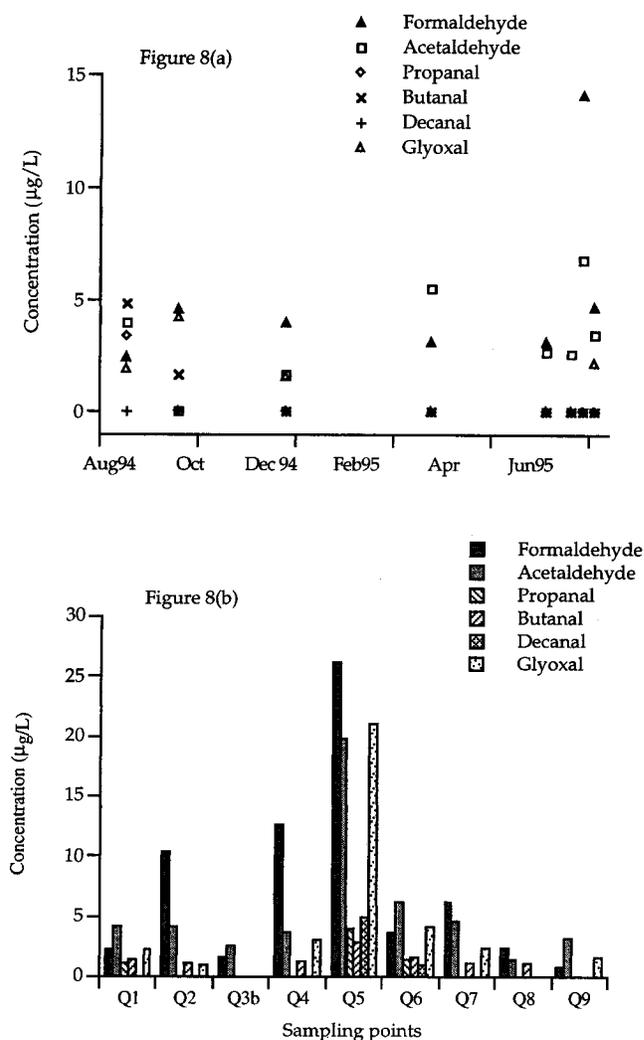


Figure 8—Aldehyde removal for 1994-1995: (a) monthly average product water concentration of aldehydes as a function of time; (b) overall formation and removal of individual aldehydes through each of the pilot plant processes for 1994-1995.

Table 5—Summary of challenge testing with *Bacteriophage*, *Giardia*, and *Cryptosporidium*.

Parameter	Primary O ₃	UF	NF	RO	Final O ₃	Total removal UF/NF
Challenge testing ^a						Log removal
<i>Bacteriophage</i>	4.0	5.3	6.4	6.7	5.1	21/22
<i>Giardia lamblia</i>	—	4.1	5.2	4.6	—	8.7/9.8
<i>Giardia</i> species ^b	—	4.8	5.3	4.4	—	9.2/9.7
<i>Cryptosporidium</i>	—	4.3	4.6	4.2	—	8.5/8.8

^a Samples were analyzed in BioVir Laboratories Inc., Benica, Calif.

^b The reagent that detected *Cryptosporidium* also detected all species of *Giardia*, not differentiating *Giardia lamblia* and *Giardia muris*.

and the drinking water should be considerably higher than the formation potential of the pilot plant product water.

Challenge testing. In this study, bacteriophage removal was determined on the primary and final ozone columns and the membrane processes. Results are summarized in Table 6 along with the results of *Giardia* and *Cryptosporidium*. Because of the superior oxidation capability of ozone, a greater than 4.0- and 5.1-log removal was observed across the primary and final ozone columns, respectively. In addition, UF and NF were each able to achieve 5.3- and 6.4-log removal, while RO achieved 6.7-log removal. Counting only one pretreatment membrane unit (either UF or NF), a cumulative removal in excess of 21-log removal was achieved. This does not take into account the ability of the clarifier, the sand and GAC filters, as well as the existing secondary treatment processes in the Grass Valley plant to remove pathogens. The effect of natural purification from detention in Lake Arrowhead and Lake Papoose, as well as removal during drinking water treatment in the Bernina plant, was ignored. While no specific regulation is presently available for virus log removal in case of surface water discharge, the required removal for groundwater recharge is 7-log removal during treatment (Hultquist *et al.*, 1991); the goal was exceeded during this study.

Giardia lamblia and *Cryptosporidium* challenge testing was performed only on the membrane processes because of the nature of detection of these two species. The feed to the unit process being challenged was spiked with the inactive seed, and the effluent from the process was filtered through a cartridge filter. The number of inactive seed microorganisms present in the filter was counted by a fluorescence assay. Because ozone disinfection is an inactivation process, unlike membrane filtration, which is a physical separation process, it was not possible to challenge the ozone columns with *G. lamblia* and *Cryptosporidium* using this method. Counting only one membrane pretreatment unit at a time, it was observed that at least 9.0- and 8.5-log removal with respect to *G. lamblia* and *Cryptosporidium* was achieved. This satisfied the treatment goal, which was 3-log removal for each of these microorganisms. *Cryptosporidium* testing was performed using Hydrofluor as the fluorescence reagent; however, the agent also detected all species of *Giardia* simultaneously, not differentiating between *G. lamblia* and *Giardia muris*. Therefore, Table 5 shows the removal of both the *Giardia* species.

Metals removal. Toward the end of the test program, samples were collected from all the sampling points (Q1 to Q9) and analyzed for the presence of metals using atomic absorption and inductively coupled plasma spectroscopy. In addition, the lake

water and the Bernina plant effluent samples were analyzed. Results of the analysis of the product water, the lake water, and the Bernina plant effluent samples are summarized in Table 6. The product water metal concentrations were equal to or below the lake and Bernina effluent levels; the removal was attributed to the presence of alum clarification and the two membrane separation units (UF/NF and RO).

Comparison of UF and NF membranes. The main difference in UF and NF membranes is the pore size distribution. NF membranes have a lower pore size cutoff (approximately 200 daltons) and are capable of removing a larger range of contaminants. Consequently, they offer better pretreatment for RO membranes. However, UF membranes generally having a higher pore size cutoff (1 000 or more) and are expected to operate at lower pressures and also not be as susceptible to fouling as NF membranes. Both these membranes were tested during this pilot program to compare performance and costs of pretreatment. It was observed that the NF was superior to UF in removing organic and inorganic constituents (di- and trivalent anions such as sulfate, phosphate, hardness, and others). This was especially important with respect to TOC, which consisted predominantly of low-molecular-weight compounds after oxidation in primary ozone columns. Product water TOC was higher when UF was operated in series with RO (Figures 8a and b); it matched the water quality goal only 75% of the time, whereas with NF/RO the product water TOC concentrations were less than the required quality goal 100% of the time. In addition, it was observed that NF was superior in removing bacteriophage and cysts (*Giardia* and *Cryptosporidium*). With respect to operating data (pressures and flux declines), both NF and UF effluent fluxes (throughput per unit area of the membrane) experienced comparable declines (around 40% decline over a period of 1 week). The RO permeate flux decline for a 4-week period was less than 10% when the feed water was UF treated and less than 5% when the feed water was NF treated. There is substantial data on operation and maintenance of the membrane units, and it will be published in the future; however, it is clear that NF provides 100% protection RO membranes.

Conclusions

A pilot plant was successfully operated in Lake Arrowhead to demonstrate that indirect potable reuse was possible. The treatment processes included were fluidized-bed denitrification, alum coagulation and clarification, sand and carbon filtration, two ozone disinfection units, and two membrane filtration units (UF/NF and RO). Intense data collection was performed for a period of 1 year; the contaminants of interest were nutrients

Table 6—Summary of results of aldehydes and metals testing.

Parameter	Approximate no. of samples	MDL ^a	Product water	Lake water	Bernina effluent
Aldehydes					
		$\mu\text{g/L}$	$\mu\text{g/L}$	$\mu\text{g/L}$	$\mu\text{g/L}$
Formaldehyde	10	1.0	3.6 ± 0.9	3.0 ± 4.0	3.4 ± 1.1
Acetaldehyde	10	—	3.0 ± 2.0	2.3 ± 1.0	12 ± 11
Propanal	10	—	<MDL	<MDL	<MDL
Butanal	10	—	<MDL	<MDL	<MDL
Decanal	10	1.0	<MDL	<MDL	<MDL
Glyoxal	10	1.0	1.6 ± 1.5	<MDL	<MDL
Metals					
		$\mu\text{g/L}$	$\mu\text{g/L}$	$\mu\text{g/L}$	$\mu\text{g/L}$
Aluminum	4	19	<MDL	33 ± 12	49 ± 9
Arsenic	4	6.0	<MDL	<MDL	<MDL
Cadmium	4	1.0	1.0	1.0	1.0
Chromium	4	1.0	1.0	2.0 ± 1.0	2.0 ± 1.0
Copper	4	2.0	<MDL	2.0 ± 1.0	<MDL
Iron	4	1.0	1.0	43 ± 40	1.0
Lead	4	5.0	<MDL	<MDL	<MDL
Manganese	4	1.0	1.0	20 ± 10	1.0
Selenium	4	5.0	<MDL	<MDL	<MDL
Silver	4	1.0	2 ± 1	2.0 ± 1.0	2.0 ± 1.0
Zinc	4	1.0	1.0	430 ± 400	340 ± 60

^a Method detection limit.

(phosphorus and nitrogen), dissolved organics, pathogens, and inorganics. Plant performance with respect to these contaminants was consistent and reliable. This was attributed to the concept of multiple barrier treatment achieved during plant operation by incorporating at least two treatment steps for each contaminant of interest. Special studies including challenge testing, aldehyde analysis, and metals testing were also undertaken, and the results indicate the technical feasibility of reuse. Minor problems were encountered with respect to nitrogen removal, but it is anticipated that the problems can be solved by incorporating better control procedures during full-scale expansion. Detailed cost estimates for a full-scale plant have not been developed; however, the costs for reclamation are less than other alternatives for the Lake Arrowhead community. This results in part because of the community's geographical location (elevation of 1 800 m), the lack of membership in the California State Project, and the cost of transporting secondary-treated water out of the basin to Hisperia.

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