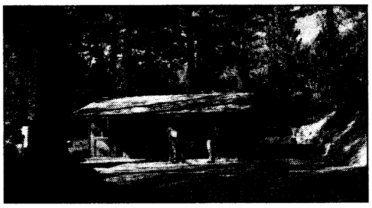


The Idyllwild Water District and Pine Cove Water District are small groundwater systems with multiple wells. Both systems have soft, mildly acidic waters with high carbon dioxide content and dissolved inorganic carbon concentrations of approximately 18 mg/L C, and both systems exceeded one or both of the lead and copper action levels in 1993 and 1994. In 1997, aeration was investigated to increase pH and replace inhibitor or other chemical additions.

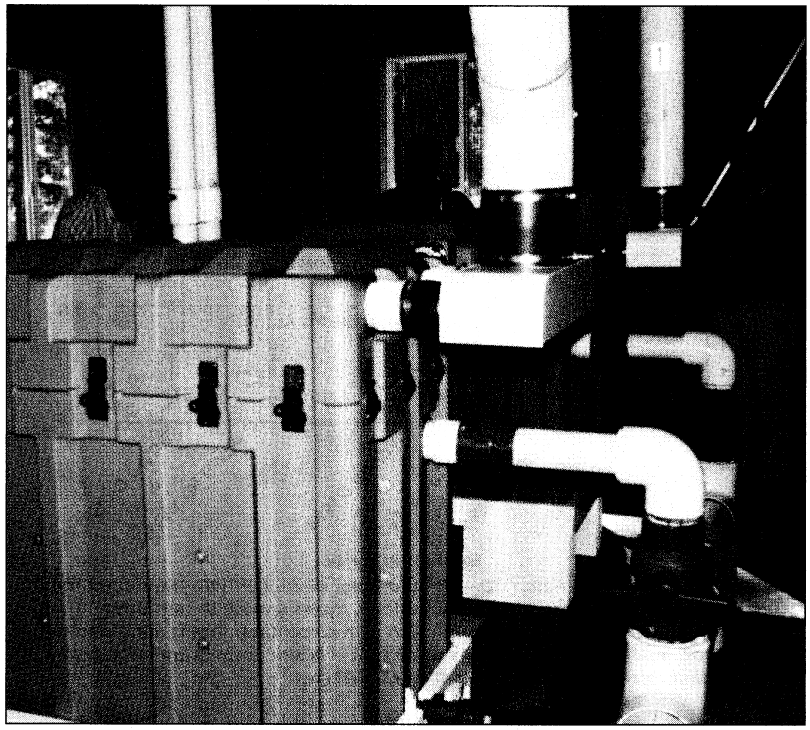
CALIFORNIA'S FIRST aeration plants for corrosion control

Four designs were evaluated, and a deep bubble aeration system was pilot-tested. Full-scale systems were designed and built and became operational in October 1998. Aeration raised the pH from 6.1–6.3 to 7.1–7.6, and by January 1999, both systems easily met both the lead and copper action levels. Radon (Rn) samples taken at Pine Cove showed a 99% reduction to 33 ± 8 pCi/L, assuring compliance with the proposed Rn regulation. Using aeration for corrosion control has considerably simplified treatment and improved water quality in most respects. Treatment was integrated with system designs, enabling the use of one treatment plant for the multiple wells at each system, locating the treatment plants above storage to eliminate repumping, and maximizing electricity savings by increasing operation at off-peak times.

BY MICHAEL R. SCHOCK, JERRY HOLLDBER, THOMAS R. LOVEJOY, AND JERRY LOWRY

As required by the Lead and Copper Rule (LCR) (USEPA, 2000; USEPA, 1994; USEPA, 1992; USEPA, 1991a; USEPA, 1991b), Idyllwild Water District (IWD) and Pine Cove Water District (PCWD) conducted a sampling and testing program in 1993 and 1994. The program began with an evaluation of local household plumbing to identify the 20 sites in each district that would be the most likely candidates for internal corrosion activity. The sampling and testing program in the IWD found that water used at the identified test sites exceeded the 90th percentile action level (AL) for copper (Cu) of 1.3 mg/L in both sampling rounds and exceeded the AL for lead (Pb) of 0.015 mg/L in June 1994. In 1993, test site water barely passed the Pb AL. Because of the absence of Pb or Cu in the source water, Pb or Cu found in the tests resulted from internal corrosion in household plumbing or fixtures.

PCWD took only one round of LCR samples because although the system met the Pb action level, it was obvious that corrosion-control treatment would be needed for Cu. Monitoring data for IWD and PCWD are summarized in the box plots in Figure 1. To attempt to reduce the Pb and Cu concentrations to below the regulatory ALs, IWD initiated a pilot corrosion-control program utilizing an orthophosphate/polyphosphate corrosion inhibitor. Because of the similarity of water in the two districts, the state of California allowed PCWD to defer action until results of the IWD pilot program were known.



Operations staff work inside the Idyllwild Water District treatment plant, a small groundwater system located in Southern California that operates multiple wells.

BACKGROUND

System descriptions. IWD and PCWD are neighboring districts located at an elevation of 5,000–6,000 ft (1,525–1830 m) in the San Jacinto Mountains of southern California (Figure 2). They are approximately 120 mi (190 km) north-northeast of San Diego and 120 miles east-southeast of Los Angeles. IWD provides water service to about 1,600 customers in its 2,400 acre (9.7 km^2) service area. PCWD serves about 1,100 customers in its 4,100 acre (16.6 km^2) service area. Customers in both districts are primarily residential customers, although IWD does have a small commercial base. All water delivered to customers in IWD and PCWD is supplied by wells penetrating fractured bedrock.

IWD. IWD operates 19 wells with a combined pumping capacity of 630 gpm (2,385 L/min). Capacities of individual wells range from a minimum of 5 gpm (19 L/min) to a maximum of 90 gpm (340 L/min). IWD has 12 ground-level storage tanks with a combined storage capacity of 3.35 mil gal (12.7 ML).

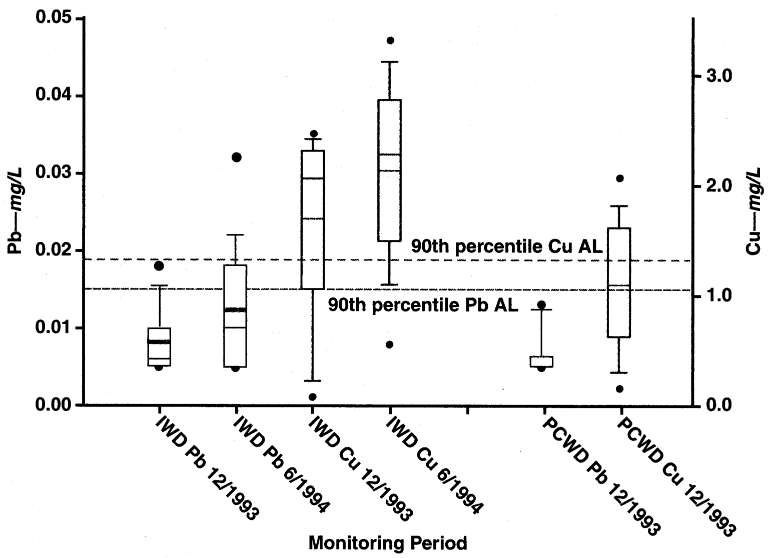
IWD's water distribution system consists of 28 mi (45 km) of pipelines ranging in diameter from 4 to 10 in. (100 to 250 mm). The great majority of the system is made up of welded steel pipe with a cement–mortar lining. A small amount of unlined steel pipe remains in older portions of the system. The distribution system consists of five pressure zones. Water is supplied from the IWD well field to storage tanks in the upper zone. Water is transferred to the main zone through a pressure-regulating station. Two small zones are supplied by pumping stations that deliver water from the main zone to the storage tanks, and the remaining zone is fed from the main zone through secondary pressure-regulating stations.

Total annual water production in IWD is about 110 mil gal (416 ML). Total production rates vary from about 150 gpm (570 L/min) in the winter months to about 350 gpm (1,325 L/min) in the warm summer months.

As shown in Table 1, the source water used by both IWD and PCWD is of very high quality, and the levels of constituents in the water are similar. This result would be expected because the source is groundwater derived from rainfall and snowmelt in the same local watershed. The water is very low in mineral constituents, particularly metals. No organic chemicals have been detected in water supplied by either district. The waters are very soft, with hardness in the range of 20 to 40 mg/L as calcium carbonate ($CaCO_3$). Because of its low pH and hardness and high carbon dioxide (CO_2) concentration, the water tends to be aggressive toward most plumbing and distribution system materials. Other than the corrosion-control treatment, the only water treatment process used in IWD is disinfection with sodium hypochlorite to provide a detectable residual level throughout the distribution system.

PCWD. PCWD produces nearly 40 mil gal (151 ML) per year from 15 deep vertical wells located throughout the district. The system is configured in such a way that 10 of the wells pump directly to the plant. Maximum pumping capacity using these 10 wells is 290 gpm (1,098 L/min), but normal usage is much lower. Pumping levels average

FIGURE 1 Box plots for initial LCR monitoring data



LCR—Lead and Copper Rule, IWD—Idyllwild Water District, PCWD—Pine Cove Water District, Pb—lead, Cu—copper, AL—action level. Boxes span 25th and 75th percentiles; whiskers represent the 10th and 90th percentiles; means are indicated by green lines; medians are indicated by solid lines in boxes; outliers are indicated by solid circles; reference lines are shown for LCR ALs.

from depths of 150–300 ft (46–91 m) in most normal rainfall years. Storage consists of six steel tanks in two locations. The upper 3 mil gal (11.4 ML) is contained in four tanks just below the new aeration plant at a higher elevation, and two tanks are located at a lower pressure zone. The system has always been gravity-fed. With the new aeration plant, all water is now gravity-fed from the new aeration plant through the main storage area to the distribution system. The distribution system consists of 19 mi (31 km) of 4, 6, and 8 in. (100, 150, and 200 mm) main lines, nearly 90% of which are steel pipe and 60% are cement–mortar-lined. The remaining 10% are polyvinyl chloride (PVC) or asbestos cement.

As at IWD, PCWD's only treatment other than corrosion control consists of adding a small amount of sodium hypochlorite to maintain a modest free chlorine residual throughout finished water storage and the distribution system. The general water quality before installation of the aeration plant is shown in Table 1.

EVALUATION OF CORROSION-CONTROL ALTERNATIVES

Prior to initiating a corrosion-control study, the IWD and PCWD carefully reviewed a broad variety of reference documents. Evaluation of alternative treatment schemes looked at capital and operating costs, simplicity of operation, the need for repumping after treatment, and the type and amount of chemical treatment required. Because of customer perception of aesthetic problems associated with a corrosion inhibitor, the districts also wanted to minimize or, if possible, avoid the use of an inhibitor.

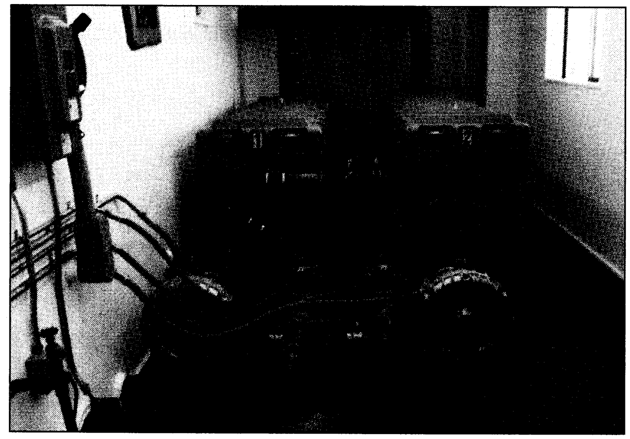
Blended phosphate treatment evaluation. Because the effectiveness of a corrosion-control program is uncertain prior to its implementation, a trial passivation program was initiated at IWD. Baseline data were established through sampling and testing water drawn from five homes at various locations in the district. From results of the first rounds of testing in 1993 and 1994, these homes were thought to have the highest probability of corrosion in their internal plumbing and fixtures. A flushing program was instituted to remove loose scale from the older water lines.

The pilot program began in April 1996 with the injection of a 50:50 blend of orthophosphate and polyphosphate at a feed rate of approximately 1.5 mg/L of product, corresponding to a target dose of 0.75 mg/L of orthophosphate as PO_4. The blend was chosen on the basis of advice from various consultants and the experiences of other water systems in the area.

The sampling and testing procedure was repeated on a bimonthly basis to evaluate the effectiveness of the selected corrosion inhibitor. The program continued with the initial dosage and blend for nine months. During this period, an intensive flushing program was in place to control the expected aesthetic problems that could result from release of old corrosion products in the pipelines. Because polyphosphates frequently are reported to have a greater tendency to remove corrosion by-products than orthophosphate formulations, the decision was made to change the inhibitor formulation. After the nine-month trial period, the inhibitor was changed to a 70:30 orthophosphate/polyphosphate blend on the recommendation of the chemical supplier, with the dose remaining at 1.5 mg/L as product (1.0 mg/L orthophosphate as PO_4). Through 1997, the product dose was gradually increased to 2.0 mg/L, yielding a target orthophosphate dose of 1.4 mg/L as PO_4.

Results of IWD's bimonthly tap sampling and testing program for the inhibitor treatment are shown in Figure 3. Water samples tested throughout the pilot program indicated that the dosing of 70:30 (ortho:poly) blended phosphate corrosion-control treatment was more effective in reducing Pb concentrations than the 50:50 blend. The effect on reduction of Cu concentrations was less consistent and was generally inadequate. Flushing appeared to be needed continually to alleviate consumer concerns, and that was labor-intensive and costly. In December 1996,

Two aeration systems have been installed in the Pine Cove District treatment plant.



after eight months of phosphate dosing, samples for total and orthophosphate were collected at three sites in the distribution system: the district office and two sites reflecting remote parts of the system. Total phosphate concentrations were 0.83, 0.74, and 0.77 mg/L as PO_4, respectively, indicating not much loss throughout the system. Corresponding orthophosphate concentrations were 0.72, 0.64, and 0.66 mg/L PO_4, respectively, suggesting that the polyphosphate concentration was very consistent, but significant reversion from the 50:50 ratio was evident.

In mid-1997, the consultant working with IWD and PCWD contacted the Treatment Technology Evaluation Branch (TTEB) of the US Environmental Protection Agency (USEPA) in Cincinnati, Ohio, requesting a review of the monitoring and treatment testing data and soliciting comments or suggestions pertaining to improving the treatment performances of the corrosion-inhibitor approach.

On the basis of accumulated knowledge about the response of Cu and Pb to orthophosphate and blended phosphate dosing (Schock & Clement, 1998; Lytle & Schock, 1997; AWWARF–TZW, 1996; Edwards et al, 1996; Lytle et al, 1996; Lytle & Schock, 1996; Schock et al, 1995a; Schock et al, 1995b; Benjamin et al, 1990; Reiber, 1989), the desired improvement could be achieved by any of three approaches:

- increasing the dosage of the corrosion inhibitor to increase the orthophosphate residual,
- elevating the pH of the source water, or
- using an orthophosphate chemical alone (possibly with some pH adjustment for Pb).

Optimum results with phosphate inhibitors for Pb are normally produced in low-hardness water with a pH in the range of 7.4 to 7.8 (Schock et al, 1996; Schock, 1990). For Cu, the optimum pH is probably slightly lower (Schock et al, 1995a; Schock et al, 1995b). Without pH adjustment, inhibitor dosage would have to be increased to a level at which orthophosphate concentrations probably would reach 3 to 5 mg/L or more. The districts believed that the modest reduction in Cu corrosion produced by increasing the inhibitor dosage would be offset by increased customer concern for the loss of purity of their pristine mountain water source.

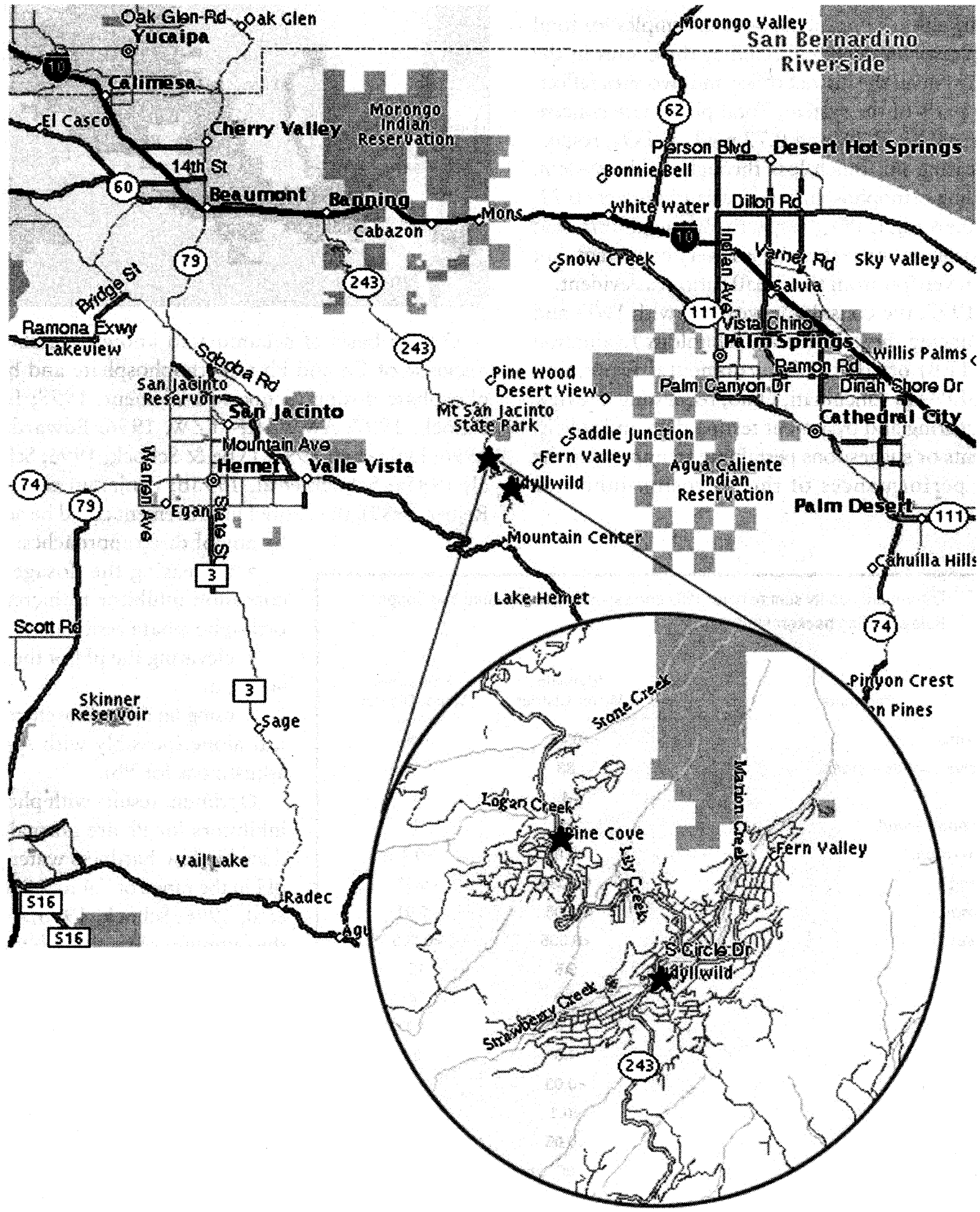
Selection of aeration. Neither system favored adding a caustic substance to elevate pH, primarily to avoid the new safety and chemical-handling considerations that would have to be implemented. Customers were also somewhat uncomfortable

TABLE 1 Entry-point quality summary for 1993 corresponding to the Lead and Copper Rule sampling background*

Parameter	Idyllwild Water District	Pine Cove Water District
Turbidity—*ntu*	0.48	0.5
Total dissolved solids—*mg/L*	88	110
Color	4	3
Threshold odor—*mg/L*	<1	1
Aluminum—*mg/L*	<0.05	<0.1
Arsenic—*mg/L*	0.0035	<0.01
Copper—*mg/L*	<0.05	<0.01
Lead—*mg/L*	<0.005	<0.005
Sodium—*mg/L*	9.5	12
Calcium—*mg/L*	8.0	14
Potassium—*mg/L*	2.0	1.4
Magnesium—*mg/L*	1.0	2
Manganese—*mg/L*	<0.03	<0.01
Total iron—*mg/L*	<0.1	0.02
Zinc—*mg/L*	<0.05	<0.01
Silica (analyzed 1998)—*mg/L*	36	42
Fluoride—*mg/L*	0.15	0.1
Chloride—*mg/L*	3	12
Nitrate—*mg/L* N	<0.07	
Nitrite—*mg/L*	<0.4	0.2
Sulfate—*mg/L*	1.5	7
pH	6.8–7.2	6.1–7.5
Total alkalinity—*mg/L as calcium carbonate*	45–65	40–80
Carbon dioxide—*mg/L* as CO_2	25–50	35–55
Dissolved inorganic carbon (computed estimate)—*mg/L as C*	18	20

*Some analyzed constituents are not included in the table. Ranges represent span for the source water wells.

FIGURE 2 Geographic setting of Idyllwild Water District and Pine Cove Water District



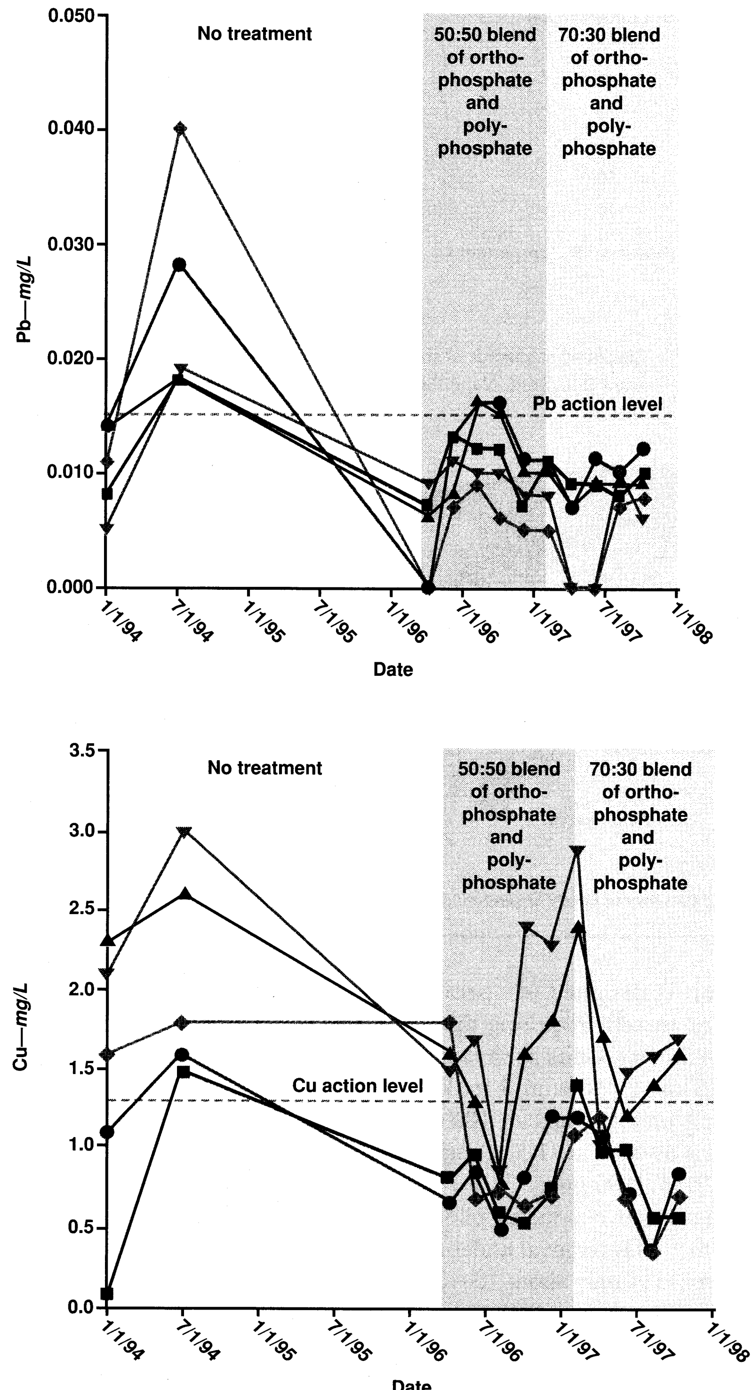
with the idea of adding any sort of treatment chemical to the water. Other potential alternatives included increasing the orthophosphate level or the use of sodium silicate to raise the pH (Schock et al, 1998). However, bearing in mind the customer concerns and after considering the raw water chemistry data and doing some treatment modeling calculations (Lytle et al, 1998a; Lytle et al, 1998b; Lytle et al, 1998c), USEPA suggested that IWD and PCWD might be nearly ideal candidates for aeration treatment. Aeration would also fit nicely with the hydraulic configurations of the two water systems.

With this approach, the districts might be able to successfully raise pH and keep dissolved inorganic carbon (DIC) low for Cu control but sufficient for pH stability. In addition, a high enough pH could potentially solve Pb release from the soldered joints and brass plumbing fixtures. At a minimum, aeration would provide a simple means for adjusting pH to a range optimal for Pb reduction by orthophosphate passivation, while enabling a high enough pH and low enough DIC concentration to adequately reduce Cu release. From the standpoint of the consumers, aeration would also be an aesthetically pleasing "nonchemical" kind of treatment. Unlike groundwater systems directly pumping anoxic source waters, the systems were already practicing chemical disinfection. Therefore, increasing the dissolved oxygen (DO) concentration would not significantly increase the redox potential of the water and thus would not cause new iron (Fe) or Cu corrosion problems because of the introduction of new oxidation (Schock, 1999; Lytle et al, 1998a; Lytle et al, 1998b; Lytle et al, 1998c; Schock et al, 1995a; Schock et al, 1995b).

As shown in Table 1, CO_2 levels in the local groundwater as determined by a field titration test kit were in the range of 25–55 mg/L. Rudimentary tests conducted at IWD in November 1997 indicated that pH could be elevated by stripping CO_2 from the source water. A bench-top test was conducted, using a raw water sample at a pH of 6.3 and containing 40 mg/L of CO_2. As CO_2 levels were reduced, pH was found to increase (Table 2). As expected, total alkalinity remained unchanged at 60 mg/L as $CaCO_3$ throughout the test. Results from this simple bench-top procedure indicated that 60% removal of CO_2 produced an increase in pH from 6.3 to 7.5. This was encouraging and suggested that the pH could be raised even further by additional stripping of CO_2.

The districts considered a tray aeration system. This system consisted of a modular air stripper supplied by a 10 hp (7.5 kW) forced-air blower. Use of this unit in IWD would require repumping equipment and construction of a weatherproof enclosure. In addition to the routine costs of operation and maintenance of the equipment, the district would also incur the cost of energy to continually operate the blower. Other alternative aeration system designs were chosen for the initial pilot investigations.

FIGURE 3 Pb and Cu levels at special monitoring sites during distribution system blended phosphate corrosion-inhibitor dosing at Idyllwild Water District



Pb—lead, Cu—copper

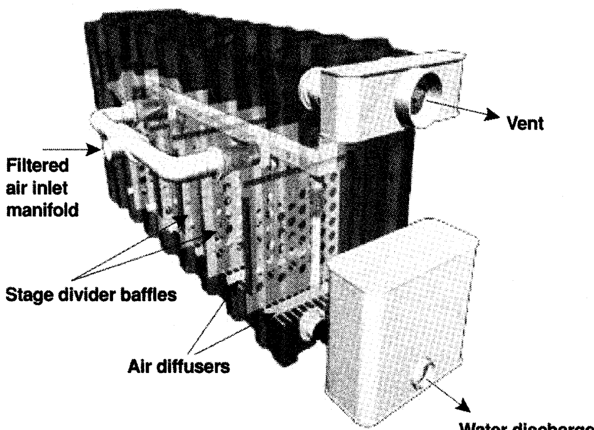
Injection system pilot test. On the basis of initial costs of the system and its size and adaptability to the vertical wells, the district gave serious consideration to selecting an air-injection system using Mazzei injectors to transfer air into pressurized water systems. The system uses Venturi injectors to introduce air prior to water entering a reactor vessel. The water is then passed into a centrifugal degassing separator where the entrained CO_2 is stripped.

TABLE 2 Relationship of pH to CO_2 level in bench-top air-stripping experiments at Idyllwild Water District*

CO_2 Concentration *mg/L*	pH
40	6.3
30	6.6
24	6.7
18	7.2
16	7.5

*CO_2—carbon dioxide, temperature = 14°C

FIGURE 4 Simplified schematic of six-stage aeration systems used at Idyllwild Water District and Pine Cove Water District



Drawing courtesy of Lowry Engineering Inc.

The unit is designed to operate with minimum back-pressure, thereby requiring that the water be repumped after treatment. Units are available in a range of sizes to handle flow rates from 5 to 3,500 gpm (19 to 13,250 L/min). A unit designed for 100 to 300 gpm (380 to 1,135 L/min) is about 5 ft (1.5 m) high and has a base diameter of 20 in. (500 mm).

The districts conducted pilot tests of this system and found that CO_2 removal under typical operational conditions would be only about 20–40% with one pass through the unit. To achieve 80–90% removal, either a series of units would be required or flow would be recirculated three or four times through a single unit. Operating in the recirculation mode would require a unit three or four times the size of a single-pass arrangement and was deemed by the districts to be somewhat difficult to operate.

Diffused bubble system test. The diffused bubble aeration unit* chosen for evaluation is shown in Figure 4. The system consists of modular aeration units that require an equipment area ranging from 60 sq ft (5.6 m^2) for two modules to 160 sq ft (15 m^2) for four modules. The number of modules needed depends on the level of CO_2 removal desired and the number and size of blowers required. One 5 hp (3.8 kW) blower is needed for each module. The equipment should be housed in a secure weatherproof enclosure.

The diffused bubble aeration unit used in the test was rented from the manufacturer and mounted on a flatbed truck so that it could be transported easily between test sites at PCWD and IWD. In March 1998, the unit was tested on two individual wells at IWD (Foster Lake well field) and on the influent line at a PCWD storage tank (Rocky Point tank). Table 3 summarizes test results for different combinations of flow rate and diffuser size. Supplemental analyses were conducted by TTEB to verify field-testing of DIC and CO_2 removal and to monitor important process water chemistry parameters that might affect suitability of aeration (e.g., Fe and hardness) and those that would affect the corrosivity of the treated water (such as DIC). These data are shown in Table 4.

For all the groundwater sources tested, the diffused bubble aeration unit was shown to provide good CO_2 removal and acceptable elevation in pH. The unit was demonstrated to be more effective at lower flow rates than the other system tested. The 200 gpm (760 L/min) test was conducted to provide an upper performance limit. Normally, the units would be operated at flow rates < 150 gpm (570 L/min). In this range of flow rates, a marked reduction in Pb and Cu corrosion would be expected.

Representatives of the California Department of Health Services (CDHS) were on hand to observe the tests and provide comments. State officials concurred with the districts' recommendation of going ahead and using aeration to reduce the CO_2 level and thereby increase the pH. At the time of the state's review, it was not clear whether increasing pH alone would reduce corrosion sufficiently to ensure compliance with the LCR or whether subsequent addition of corrosion inhibitor would still be required.

FULL-SCALE IMPLEMENTATION

In the development and implementation of a corrosion-control treatment scheme, the physical layout of the distribution system may be a significant factor in determining the cost and quality of the finished water. Careful planning can result in substantial long-term cost and operations savings, as well as better water quality and convenience for the water system operators.

In this case, PCWD, faced with a need for more water volume and Cu corrosivity problems that would require the addition of new treatment, first studied the feasibility of buying and laying the necessary pipe to connect four of its wells. From there, the district could pump to a common point where the water could join water already produced by consolidation of nine of the nearby wells and then proceed to the final treatment and gravity feed to storage and distribution. PCWD staff proposed the four-well consolidation to its board, which approved the expenditure.

The first phase totaled approximately \$75,000 for nearly 3,000 ft (914 m) of 4 in. (100 mm) cement–mortar-lined steel pipe; the cost included trenching, equipment rental, road repair, permits, easements, and all labor. A second phase was estimated at \$14,000 for an additional 4,000 ft (1,220 m) of 2 in. (50 mm) PVC pipe, including material, equipment, and labor. With this consolidation, PCWD eliminated the need for three additional aeration treatment plants. Thus, a short-term expenditure saved more than twice its cost in treatment facilities that would be needed in the future and also eliminated the extra maintenance and operation complexity of additional treatment plants. Furthermore, by having 13 of the 15 wells flowing through one common loading line, the district could chlorinate at a single point prior to aeration.

The Pine Cove and Idyllwild aeration system units are close to being identical in design, having the principal design characteristics shown in Table 5. The system at each site consists of two aeration vessels† and two regenerative blowers. The flow rate is split between the two parallel aeration vessels. Each blower gives 245 cu ft/min (6.9 m^3/min) at 25 in. water column, for a total of 490 cu ft/min (13.9 m^3/min). The blower motor is 5 hp (3.7 kW). The aeration vessel is a low-profile multistage (six stages) unit constructed of polyethylene, PVC, and type 316 stainless steel. Flow is by gravity, and discharge is to atmospheric storage. Inlet air is filtered at 10 µm, and vent air is discharged outdoors.

The costs of equipment and construction of the two treatment plants is summarized in Table 6; the facilities and operation are described in subsequent sections.

TABLE 3 Pilot test of the effect of different diffuser sizes and flow rates on pH and carbon dioxide removal for the six-stage aeration systems

Test Results Using 0.625 in. (15.9 mm) Diffuser

Test Site	Flow Rate *gpm (L/min)*	Raw pH	Treated pH	Carbon Dioxide—*mg/L as CO_2* Raw	Treated	Removal %
IWD* well 5	45 (170)	6.54	7.42	28	3.4	88
IWD well 2	100 (380)	6.72	7.50	18	3.0	83
IWD well 2	200 (760)	6.72	7.31	18	4.8	73
PWCD†	100 (380)	6.60	7.20	28	7.2	74

Test Results Using 0.030 in. (0.8 mm) Diffuser

Test Site	Flow Rate *gpm (L/min)*	Raw pH	Treated pH	Carbon Dioxide—*mg/L as CO_2* Raw	Treated	Removal %
IWD well 5	45 (170)	6.54	7.68	28	1.8	94
IWD well 2	100 (380)	6.72	7.51	18	2.6	86
IWD well 2	200 (760)	6.72	7.32	18	4.5	75

*IWD—Idyllwild Water District
†PCWD—Pine Cove Water District

TABLE 4 Analyses of water during pilot test of aeration systems

Analyte	IWD* (Raw)	IWD (Postaeration)	PCWD† (Raw)	PCWD (Postaeration)
Aluminum—*mg/L*	0.06	0.05	<0.025	<0.025
Calcium—*mg/L*	8.56	8.79	9.2	9.22
Copper—*mg/L*	0.01	<0.01	<0.01	<0.01
Iron—*mg/L*	0.16	0.21	0.01	0.05
Potassium—*mg/L*	1.40	1.38	1.48	1.52
Magnesium—*mg/L*	1.13	1.09	0.83	0.82
Manganese—*mg/L*	0.06	0.07	<0.01	<0.01
Sodium—*mg/L*	10.1	9.7	10.4	10.2
Zinc—*mg/L*	0.02	0.01	0.11	0.11
Alkalinity—*mg/L as calcium carbonate*	42.6	42.7	44.3	44.4
Sulfate—*mg/L SO_4*	1.24	1.25	0.93	0.93
Chloride—*mg/L*	3.9	5.6	4.1	4.5
Silica—*mg/L SiO_2*	36.5	37.1	41.8	41.4
Nitrate + Nitrite—*mg/L N*	0.04	<0.02	0.42	0.43
Orthophosphate—*mg/L PO_4*	0.29	0.29	0.13	0.13
Total inorganic carbon—*mg/L C*	18.34	12.29	20.28	12.30

*IWD—Idyllwild Water District
†PCWD—Pine Cove Water District

Idyllwild aeration plant. In August 1998, IWD completed construction of its aeration treatment facility and the plant went on line in October 1998. The facility consists of the two diffused bubble aeration units† housed in a 450 sq ft (42 m^2) building. Air-intake piping brings in filtered outside air to the blowers, with exhaust piping arranged to prevent short-circuiting of CO_2 to the intakes. The building was constructed at an elevation a few feet above the high water level of the district's storage tanks. Water is discharged from the aeration plant to the tanks

*DeepBubble™ System, Lowry Aeration Systems, Blue Hill, Maine
†Model DW6 DeepBubble™ System, Lowry Aeration Systems, Blue Hill, Maine

by gravity, thus eliminating the need for repumping treated water.

Because the aeration system is in full-time operation, it is operated with a very simple manual control system. In winter, when flows are less than 200 gpm (760 L/min), only one unit is in operation. Summer demands require that both units be in full-time operation for four to six months. The peak summer flow rate through the two parallel units is currently about 350 gpm (1,325 L/min). The building housing the units is designed with adequate space so that a third aeration unit can be added as demand increases.

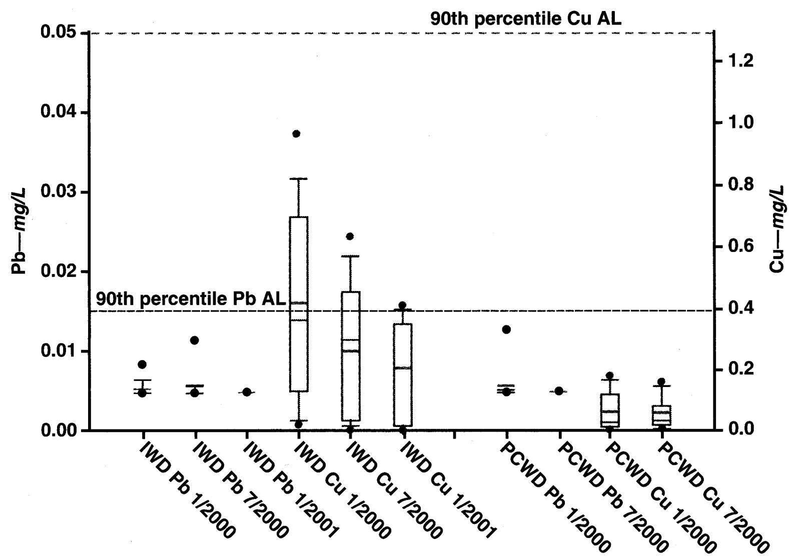
Pine Cove aeration plant. PCWD has two diffused bubble aeration units* located at the Rocky Point Tank Farm. The units along with the blowers, necessary piping, electrical system, and small testing laboratory are located in a 240 sq ft (23 m^2) steel container. To enable complete gravity-fed treatment operation, water levels in the aeration units are 20 ft (6.1 m) above high water level in the storage tanks. All water is pumped from 10 wells directly to the aeration plant and then gravity-fed to the storage and distribution systems. Sodium hypochlorite is added at a well site prior to the aeration plant to enable disinfection through treatment. The maximum collective pumping from the 10 wells is 290 gpm (1,100 L/min), although average system demand is usually much less. The plant went on line Oct. 9, 1998, and has been in continuous operation ever since.

WATER QUALITY AND OPERATIONAL EFFECTS

IWD. The first round of post-treatment installation Pb and Cu samples was conducted in January 1999, three months after initial operation commenced. Six months later, a set of repeat samples was taken, followed in July 2000 by a

*Model DW6 DeepBubble™ System, Lowry Aeration Systems, Blue Hill, Maine

FIGURE 5 Box plots for LCR monitoring data after aeration treatment installation



LCR—Lead and Copper Rule, IWD—Idyllwild Water District, PCWD—Pine Cove Water District, Pb—lead, Cu—copper, AL—action level. Boxes span 25th and 75th percentiles; whiskers represent the 10th and 90th percentiles; means are indicated by green lines; medians are indicated by solid lines in boxes; outliers are indicated by solid circles; reference lines are shown for LCR ALs.

TABLE 5 Comparison of the design performance characteristics of PCWD and IWD*

Utility	Design Flow *gpm (L/min)*	Design Air-to-Water Ratio	Expected Carbon Dioxide Removal at 0°C—%
PCWD	300 (1,136)	12.2	93
IWD	280 (1,060)	13.1	94

*PCWD—Pine Cove Water District; IWD—Idyllwild Water District

TABLE 6 IWD and PCWD aeration plant construction costs*

Item	Cost—$ IWD	Cost—$ PCWD
Materials		
Two aeration units with blowers	18,835	15,200
Inside piping, valves, meters	2,755	4,456
Outside piping	5,520	5,483
Subtotal, materials	27,110	25,139
In-house labor		
Site preparation, construction of outside and inside piping, installation of units	10,195	16,285
Outside contracts		
Building/enclosure	12,680	5,877
Electrical controls and lighting	9,975	4,122
Outside labor, engineering, materials		20,967
Subtotal, outside contracts	22,655	30,966
Total construction cost	59,960	72,390

*IWD—Idyllwild Water District; PCWD—Pine Cove Water District

TABLE 7 Distribution system water quality information obtained in Aug. 29, 2000, sampling in PCWD*

Location	pH	Free Chlorine Residual *mg/L as Cl_2*	Temperature *°C*	Dissolved Oxygen *mg/L as O_2*	Distance From Storage Tank 1 *ft (m)*	Distribution System Pipe Sequence
Tank 1	7.3	0.28	15.6	8.25		†
PCWD office	7.2	0.24	20.0	7.91	2,000 (610)	8 in (200 mm) PVC‡ main
Marion Ridge	7.3	0.20	17.8	6.09	5,000 (1,524)	8 in. (200 mm) PVC main
Highway Tank	7.4	0.21	18.9	7.85	3,500 (1,067)	8 in. (200 mm) PVC to 4 in. (100 mm) steel
Dutch Flats	7.4	0.15	18.9	7.58	10,000 (3,048)	8 in. (200 mm) PVC to 8 in. (200 mm) CML§ iron to 4 in. (100 mm) steel
Sylvan–Nestwa	7.5	0.10	18.9	6.15	5,000 (1,524)	8 in. (200 mm) PVC to 6 in. (150 mm) CML iron
Acorn	7.5	0.12	18.9	7.51	6,000 (1,830)	8 in. (200 mm) PVC to 6 in. (150 mm) CML iron

*PCWD—Pine Cove Water District
†Tank 1 is the fourth tank in the main storage sequence following aeration, equivalent to 3 mil gal (11.4 ML).
‡PVC—polyvinyl chloride
§CML—cement-mortar-lined

round of 10 samples. Results of the postaeration LCR monitoring results are shown in Figure 5. Since the installation of the aeration treatment, Pb levels have been comfortably under ALs, and Cu levels have decreased continually. These results indicate that aeration alone is sufficient to produce satisfactory results in compliance with the LCR.

Distribution system pH measurements at five sites in July 2000 showed a range of 7.4 to 8.2, with the high pH probably resulting from dissolution of cement linings in the soft water. IWD has been able to discontinue its use of a corrosion-control inhibitor and achieve improved results, reduced chemical costs, and greater customer satisfaction. Comparison of winter and summer Cu tests indicates that cuprosolvency is reduced during summer operation when both units are on line. This is probably the result of the increase in air-to-water ratio resulting from the lower flow rate in each unit. Additionally, other researchers have noted significant decreasing of Cu levels over time during an "aging" process as passivating films develop and evolve (Edwards et al, 2001; Schock et al, 2000; Schock et al, 1995a; Schock et al, 1995b). Idyllwild periodically has small increases in raw water Fe and manganese (Mn), which becomes noticeable in the aeration process. Increased Fe levels and consequent ferric oxyhydroxide precipitation can decrease the final pH level achievable without supplemental treatment.

Two aeration units easily handle the range of flows from 150 to 350 gpm (570 to 1,325 L/min). Because IWD wells are operated around the clock, aeration units operate continuously as well. The plant requires minimal operator attention. Water system operators make a routine daily visit to observe equipment operation and record operating data. When a change is noted in intake air pressure, air filters are cleaned or changed. The main component of operating cost is the cost of power to operate the blowers. At IWD, this cost has ranged between $200 and $400 monthly.

PCWD. Samples were collected for Pb and Cu in January and July of 1999. Even samples collected only three months after startup showed excellent results, as shown in Figure 5. Effluent water pH tests show pH of 7.4 to 7.8 is the normal product water composition, varying with raw water pH and CO_2 content. Sampling at customer taps in the distribution system generally has shown pH from 7.6 to 8.8. High pH values represent water that has passed through cement–mortar-lined distribution mains.

After initial startup, a monthly program was established to check air filters, inspect the inside of aeration boxes, clean the inside of the building, and perform numerous tests to ensure the process is still working properly. The in-house labor averages only 3 to 4 h per month. There have been no shutdowns or interruptions resulting from mechanical problems. With the cooperation of Southern California Edison, PCWD has changed all of the electrical accounts on wells and the aeration plant to a special rate schedule. This new off-peak charge is set at $0.05543 instead of $0.11760 per kW·h, a nearly 60% reduction. In July, the highest production month, 5.4 mil gal (20 ML) of water was produced. Electric costs average $5.18 per day or just $0.029/1,000 gal ($0.007/1,000 L).

On Aug. 29, 2000, after the aeration plant had been continually operating for nearly 23 months, an additional investigation was undertaken to evaluate the stability of water quality in the PCWD distribution system and the CO_2 removal efficiency of the treatment plant. Samples for complete chemical analyses were taken by PCWD staff immediately preceding and following the aeration system and immediately sent to TTEB in Cincinnati. Total inorganic carbon (TIC, assumed equal to DIC although not actually filtered) samples were taken in duplicate. PCWD staff also took field measurements for temperature, pH (glass electrode), DO (electrode), and free chlorine residual (spectrophotometric). Additionally, PCWD staff took field measurements immediately thereafter at seven

TABLE 8 Analyses of water and effects of aeration obtained during Aug. 29, 2000, process evaluation at Pine Cove Water District

Analyte	Raw Water	Postaeration
Calcium—*mg/L*	9.2	9.2
Potassium—*mg/L*	1.5	1.5
Magnesium—*mg/L*	0.83	0.82
Sodium—*mg/L*	10.4	10.2
pH (field)	6.6	7.8
pH (computed)*	6.44	7.8
Temperature—*°C*	13.3	13.3
Alkalinity—*mg/L calcium carbonate*	52.4	52.2
Sulfate (estimated)†—*mg/L* SO_4	0.93	0.93
Chloride—*mg/L*	4.1	4.5
Silica—*mg/L SiO*	41.8	41.4
Nitrate + Nitrite—*mg/L N*	0.42	0.43
Orthophosphate—*mg/L* PO_4	0.13	0.13
Total inorganic carbon—*mg/L C*	24.57	13.16
Computed* carbon dioxide (CO_2) (aqueous)—*mol/L*	9.84×10^{-4}	4.31×10^{-5}
Computed* CO_2 (aqueous)—*mg/L* CO_2	43	1.9
Computed* CO_2 removal—*%*	NA‡	96
Computed* ionic strength	0.0016	0.0016
Computed* ion balance error—*%*	–1.2	–1.7

*Computed using the WATEQX chemical equilibrium speciation program
†Estimated from previous analytical data. Low ion balance error suggests that this estimate was reasonably accurate for the purposes of this investigation.
‡NA—not applicable

other system locations; sampling results are summarized in Tables 7 and 8. The tank 1 site essentially represents the entry point to the distribution system, following 3 mil gal (11.4 ML) of storage spread through four tanks. Both pH and free chlorine residual are very stable in the distribution system, and excellent Cu and Pb control are maintained in the presence of substantial DO, which has been shown to be theoretically possible (Edwards et al, 1996; Ferguson et al, 1996; Schock et al, 1996; Schock et al, 1995a: Schock et al, 1995b).

Data evaluation. Because all three interrelated parameters—pH, DIC, and total alkalinity—were measured and because substantial historical data have been collected over several years in the USEPA laboratory on the precision and accuracy of both acidimetric total alkalinity titrations (to the carbonic acid equivalence point) and coulometric TIC analyses (Schock & George, 1991), the accuracy of the field pH measurements could also be estimated from fundamental aquatic chemistry relationships (Butler & Cogley, 1998; Stumm & Morgan, 1996; Butler, 1982). To do this and to compute the removal efficiency of CO_2 from the water, the complete analytical data set was input into the WATEQX geochemical equilibrium model computer program (van Gaans, 1989). Equilibrium constant data in the program database for relevant complexation and acid-base reactions were critically evaluated by the senior author and were set to be consistent with those used in previous aeration chemistry research (Lytle et al, 1998a; Lytle et al, 1998b; Lytle et al, 1998c).

Calculations were performed with WATEQX using DIC input to compute total alkalinity and total alkalinity input to compute DIC. As noted previously, all TIC in the water samples was assumed to be dissolved; therefore, DIC = TIC in the calculations. As shown in Table 8, total alkalinity was conserved during the aeration process within expected analytical error, consistent with chemical theory. Calculations showed that DIC, pH, and total alkalinity were all consistent within analytical uncertainty for the postaeration water. However, given the field pH of 6.6, there was a substantial discrepancy between DIC and total alkalinity for the raw water (10 mg/L as $CaCO_3$ for alkalinity, 3.8 mg/L DIC as C). Also, the ion balance error for the water analysis was a suspiciously large value of > –8.4% when DIC input was used, which is normally the most accurate and precise of the three analyses. Other ion balance errors were close to only ± 1%.

Experience with field measurements suggests that pH is the most difficult analysis of the three and the most susceptible to bias or analytical error. Therefore, to test the hypothesis that the pH might be biased by being measured with air contact, additional calculations were performed with different initial pH values. These showed that if the pH was only slightly different (6.44), both total alkalinity and DIC values became consistent well within the laboratory's documented analytical error. This follows well with the expected direction of the bias of a high-CO_2 water exposed to the atmosphere during even a good field pH measurement (Schock et al, 1980) and with earlier measurements of the raw water at PCWD during exploratory testing. Therefore, when the estimated pH of 6.44 (rather than 6.6) is used, CO_2 removal efficiency was 96%, almost exactly what would be expected from the design of the diffused bubble system and predicted by general carbonate equilibria expressions commonly applied to aeration (Lytle et al, 1998a; Lytle et al, 1998b; Lytle et al, 1998c).

Radon (Rn) removal investigation at PCWD. Aeration is widely known as an effective treatment for Rn removal. The geological and geochemical settings of PCWD and IWD are similar to those in areas of New England known to have significant groundwater Rn contamination problems. To explore PCWD's possible future status relative to new water Rn regulations, duplicate samples were taken Mar. 15, 1999, for Rn analysis from the raw influent water and from the aeration treatment effluent. The average values showed the aeration system produced a 99% Rn reduction (from 3,738 ± 8 pCi/L to 33 ± 8 pCi/L), a dramatic improvement that ensured PCWD would meet any currently proposed Rn standard. Interestingly, the Rn removal efficiency observed was slightly higher than the amount observed for CO_2 (96%), which is exactly what would be expected for Rn removal by diffuse bubble aeration. This observation supports the suggestion (Spencer & Brown, 1997) that CO_2 removal is an excellent and economical surrogate for monitoring Rn gas removal from drinking water by aeration.

CONCLUSIONS AND FUTURE INVESTIGATIONS

For water systems with aggressive water having low alkalinity, low hardness, low Fe, and low pH, diffused bubble aeration has proved to be an appropriate means of corrosion control. This study provided practical evidence that Pb and Cu corrosion control can be satisfactorily accomplished in disinfected waters (even with the increases in DO brought about by the air contact) and without any observed detrimental effect on the corrosion of distribution system iron piping. Additionally, groundwater systems with excessive Rn levels and comparable pH and DIC conditions can simultaneously achieve corrosion control and very effective Rn reduction. Rn removal effectiveness has been shown to closely relate to CO_2 removal, so monitoring would be straightforward for both objectives. Because of the demonstrated performance of the aeration system by the regulatory monitoring program, the CDHS accepted the process for use at both IWD and PCWD.

PCWD consumer response. The aeration process has been embraced by consumers in both mountain communities because desired results are produced without the addition of chemicals. Since the aeration process was installed at PCWD, a white cloudiness of unknown origin that had previously appeared in the water on occasion has disappeared completely. Because of this improvement in water clarity and the absence of additional treatment chemicals aside from the disinfectant, customer feedback indicates that consumers believe their water is even better now.

At IWD, increases in background Fe and Mn concentrations in the raw water are prompting further investigation of the cost and feasibility of installing an Fe and Mn removal pretreatment system, because the chlorination/aeration process is known to be susceptible to causing red or black water problems when significant reduced Fe, Mn, or both exist in the groundwater. At PCWD, several alternative approaches are being considered for pilot investigation—to provide for future increases in water demand from population growth or low water yield from continuing drought conditions—that could necessitate using groundwater containing higher natural Fe levels. These future investigations may examine the costs and feasibility of additional wells being drilled and the water brought to the central treatment plant, additional aeration plants

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located at other well fields, the feasibility of Fe sequestration (possibly by chlorination–silicate sequestration), or the feasibility of adding filtration for Fe and Mn removal at some postaeration location. The advantage of silicate sequestration would be heightened pH and improved protection of cement-lined pipes (LeRoy et al, 1996); cement-lined pipes have been noticed to increase the pH in parts of the distribution system, indicating some dissolution in the soft water. At this time, the optimum composition of sequestrant, dosage, and location for application cannot be determined and would require actual pilot-testing to determine the most judicious design tradeoffs.

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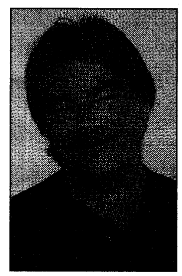

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