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ABSTRACT: Results from a five-year study indicate that the use of reclaimed water for food crop irrigation is safe and acceptable. No soil or groundwater quality degradation occurred. Conventional farming practices were adequate, excellent crop yields were obtained, and there were no obstacles to the marketability of the produce. There was no accumulation of heavy metals in the crops or soil; chlorine residuals had no observable effect on crops, and dechlorination was not necessary. *Res. J. Water Pollut. Control Fed.*, **62**, 216 (1990).

KEYWORDS: agriculture, food, heavy metals, municipal effluent, pathogens, reuse.

The Monterey Wastewater Reclamation Study for Agriculture (MWRSA) was a 10-year, $7.2 million field-scale project designed to evaluate the safety and feasibility of irrigating food crops (many eaten raw) with reclaimed municipal wastewater. During the early planning stages, Castroville, Calif., was selected as the site for the project and an environmental assessment was completed. Next, a field-scale pilot treatment plant was designed and constructed, and the experimental field plots were established in June 1980. The 5-year field study began in late 1980 and continued through 1985. During those 5 years, a perennial crop of artichokes was grown along with rotating annual crops of celery, broccoli, lettuce, and cauliflower. Extensive sampling of water, soil, and plant tissues was conducted during the field studies. Subsequent to the field studies, concluding efforts included overall statistical analysis of the field data, continued operation of the pilot treatment facilities for process optimization and virological seeding experiments, estimation of the cost of reclaimed water, and preparation of the final report. The MWRSA—Final Report[1] was published in April 1987.

The objectives of the study are listed below:

- Evaluate the safety of irrigation with reclaimed municipal wastewater for both consumers and farm workers with respect to
  - —Virus survival on crops and in soils;
  - —Cadmium and other trace element levels in edible crops;
  - —Pathogenic bacteria in irrigation waters, on crops, and in soils; and
  - —Aerosol transmission of pathogenic bacteria and viruses.
- Evaluate the effects of irrigation with reclaimed wastewater on
  - —Soil degradation due to the accumulation of heavy metals and salts or impaired soil permeability; and
  - —Yield and quality of crops.
- Evaluate consumer acceptance and economic feasibility of irrigation with reclaimed municipal wastewater.
- Provide design criteria for full-scale wastewater reclamation and reuse implementation.
- Provide field operational experience with the use of reclaimed municipal wastewater for food crop irrigation.

Large portions of the Monterey Regional Water Pollution Control Agency (MRWPCA) service area lie within the agricultural areas of the lower Salinas Valley (Calif.), as shown in Figure 1. Soils of the region are fertile, but principal limitations on agriculture are problems with drainage and seawater intrusion into coastal aquifers due to overdrafting of groundwater. There is thus an increasing shortage of irrigation water.

Four sites were studied before the final location was selected for the experimental plots and demonstration fields. The demonstration fields were used to study full-scale farm practices using reclaimed municipal wastewater. The experimental plots were used to provide large amounts of data on crop response for statistical analysis.

The climate of northern Monterey County is generally cool and moist. Cool, rainy winters are followed by cool, often foggy summers with little precipitation. Average temperatures vary little throughout the year, ranging from about 10 to 18°C. Thus, the annual growing season is year-round. The combination of fertile soils and a long growing season makes this county a rich agricultural region. In the Castroville area, about 4000 ha of land overlying the 55-m aquifer have been affected by seawater intrusion, which is progressing at the rate of about 100 ha/a. Seawater intrusion has affected about 1240 ha of the 120-m aquifer, where the intrusion rate is somewhat lower at 50 ha/a.

Pilot Treatment Plant

The existing 1500-m^3/d MRWPCA Castroville wastewater treatment plant was upgraded to provide reclaimed water for the MWRSA. The Castroville wastewater treatment plant consisted of primary sedimentation followed by a "roughing" filter and a complete-mix activated sludge basin that used three mechanical surface aerators, and then secondary sedimentation. Secondary effluent from the Castroville treatment plant was pumped to the pilot tertiary reclamation plant[2] which consisted of two parallel treatment process trains: a complete treatment process known as the "Title 22 (T-22) process" based on the California Code of Regulations Title 22, Division 4, Wastewater Reclamation Criteria,[3] and a direct filtration process, known as "filtered effluent (FE) process." Figure 2 shows schematic diagrams of the two tertiary treatment systems used in the MWRSA. The T-22 process included coagulation, clarification, filtration, and disinfection; the full treatment process stipulated spray irrigation of food crops. Doses of alum (50 to 200 mg/L) and

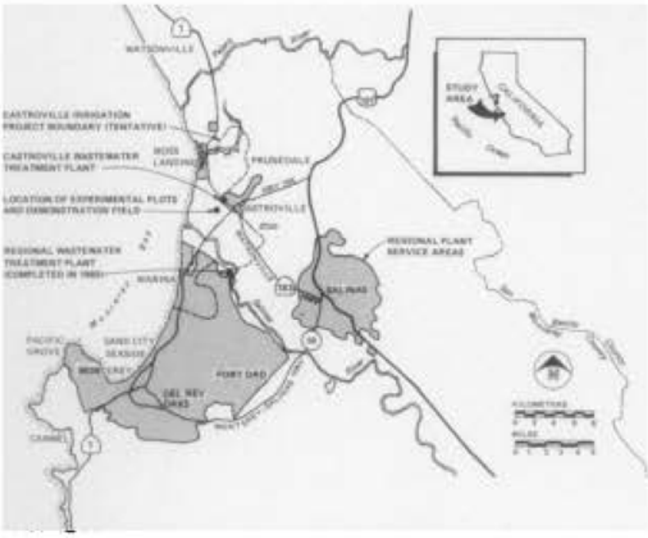

Figure 1—Location of the Monterey Wastewater Reclamation Study for Agriculture and the Monterey Water Pollution Control Agency service area.

polymer (0.2 mg/L) were used in the T-22 flow stream. The FE process included the addition of low doses of alum (0 to 15 mg/L) and polymer (0 to 0.18 mg/L) as a chemical coagulant aid with a combination of either static mixer or mechanical rapid mixing, and dual-media gravity filtration at 3.4 $L/m^2 \cdot s$. The disinfection tank using chlorine was designed with a 90-minute theoretical detention time. In October 1983, flocculation chambers were added to the FE process to enhance floc formation prior to filtration. This filtered effluent flow stream, with the flocculator in operation, is denoted as FE-F.

A summary of the California Wastewater Reclamation Criteria relevant to agricultural and landscape irrigation is shown in Table 1. Dechlorination of final effluent using sulfur dioxide was practiced during Years 1 through 3 of MWRSA, but was discontinued in June 1983 to ascertain any effects of a chlorine residual on the crops and to prevent microbial regrowth. No adverse effects of any kind were noted. Further microbial regrowth in storage tanks and pipelines was prevented. Table 2 shows operational characteristics of the two treatment plant effluents.

Demonstration Fields

Demonstration of farm-scale feasibility of using reclaimed water is one of the main objectives of the MWRSA and is of special importance to the growers, farm managers, and operators responsible for day-to-day farming practices. To investigate large-scale feasibility of using reclaimed wastewater, two 5-ha plots in the vicinity of the experimental site were dedicated to reclaimed water irrigation, using the FE flow stream. On one plot artichokes were grown; on the other plot, a succession of broccoli, cauliflower, lettuce, and celery was raised during the first 3 years of the field investigation. The crops thus raised were observed carefully for appearance and vigor. Normal farming practices of local growers were duplicated on these fields. Because of its experimental nature, the produce from these plots was not marketed. At the end of each season, they were plowed under and incorporated into the soil. Six field observation days were held,

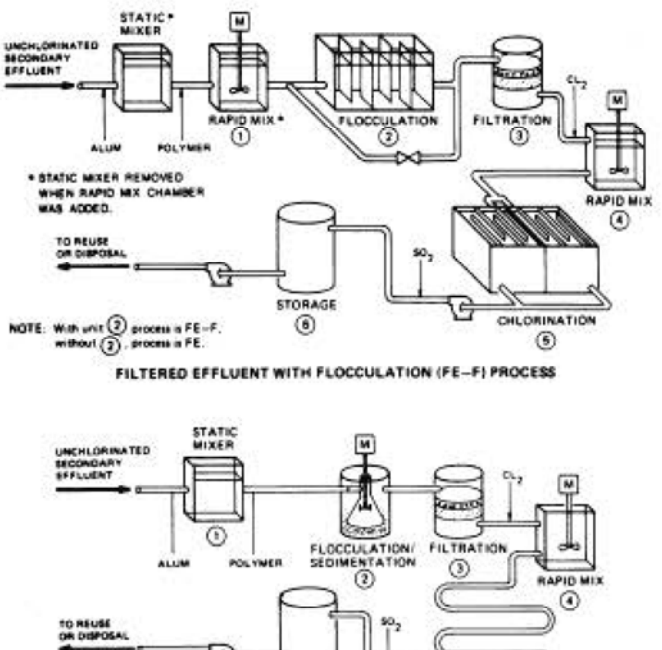

Figure 2—Schematic diagrams of tertiary treatment systems used in the MWRSA.

Table 1—Wastewater treatment and quality criteria for irrigation (California Wastewater Reclamation Criteria).[a]

Treatment	Total coliform limits (median)	Type of use allowed
Primary	—	Surface irrigation of orchards and vineyards, fodder, fiber, and seed crops.
Oxidation and disinfection	≤23/100 mL	Pasture for milking animals. Landscape impoundments. Landscape irrigation (golf courses, cemeteries, and so on).
	≤2.2/100 mL	Surface irrigation of food crops (no contact between water and edible portion of crop).
Oxidation, coagulation, clarification, filtration,[b] and disinfection[c]	≤2.2/100 mL; max = 23/100 mL	Spray irrigation of food crops. Landscape irrigation (parks, playgrounds, and so on).

[a] An excerpt from Reference 3.

[b] The turbidity of filtered effluent cannot exceed an average of 2 turbidity units (NTU) during any 24-hour period.

[c] This combination of processes is often referred to as a T-22 process as noted in the text.

Table 2—Lognormal mean concentrations of BOD_5, total suspended solids, and turbidity in treatment plant effluents (in mg/L unless otherwise noted).

	Process optimization		Year 5		Year 4		Year 3		Year 2		Year 1	
Parameters[a]	Number of samples	Mean[b]	Number of samples	Mean	Number of samples	Mean	Number of samples	Mean	Number of samples	Mean	Number of samples	Mean
BOD_5												
SE	115	12	74	14	54	11	60	8	54	8	18	22
Total suspended solids												
SE	157	14.3	302	13.4	282	11.2	228	10.2	220	8.7	192	12
FE	—	—	—	—	131	1.9	202	1.5	216	2.2	188	4.4
FE-F	155	1.2	286	1.6	132	1.5	—	—	—	—	—	—
FC	153	5.8	275	4.4	263	5.7	220	4.9	217	4.3	191	6.1
T-22	153	1.0	273	0.8	258	1.3	220	1.0	214	1.2	190	1.9
Turbidity[c]												
SE	155	3.7	288	3.8	217	3.2	212	3.6	218	2.9	—	—
FE	—	—	—	—	102	1.4	209	1.1	213	1.4	178	2.4
FE-F	152	0.7	282	1.1	103	1.0	—	—	—	—	—	—
T-22	149	0.5	262	0.6	195	0.9	205	0.6	211	0.5	183	0.6

[c] Nephelometric turbidity units (NTU).

[b] Means are 50th percentile values from probability distribution analyses. Data are fitted to the Pearson Type III lognormal distribution.

Key: [a]SE = secondary effluent; FE = filtered effluent without flocculator (September 1980–September 1983); FE-F = filtered effluent with flocculator (October 1983–April 1986); FC = flocculator-clarifier effluent; and T-22 = Title-22 effluent.

and the local growers and the news media were invited to acquaint the agricultural community with wastewater reclamation, and obtain feedback regarding their perceptions, questions, and concerns. Because adequate data on large-scale feasibility were obtained in the first 3 years of the study, irrigation of the demonstration field was discontinued in Years 4 and 5 of the MWRSA field operations.

Experimental Plots

Experimental design. A split plot design was chosen for the experimental plots. This design allowed the use of two treatment variables: irrigation water type (T-22 process effluent, FE process effluent, and well water), and fertilization rate (no fertilizer, and 33, 66, and 100% of full local fertilizer rate). Figure 3 shows the arrangement of experimental plots and irrigation water types. Spacing between the main plots was designed to avoid overspray of one water type to another by wind drift.

This experimental design allowed simultaneous comparison of effects of irrigation with different water types and varying fertilization rates. An important aspect of irrigation with reclaimed water is the nutrient value of the effluent to crops. The fertilization rates were designed to quantify the nutrient value of the two types of effluent as a supplement to fertilization. The rates of fertilizer application varied with each crop, but they were always based on the standard practice in the area. The rates also varied each year because farmers in the area typically revised the amount of fertilizer they applied as a result of the observed yields resulting from the prior year's fertilizer applications.

Agricultural practices. Artichokes, a perennial crop, were grown in the experimental fields from May 1980 until May 1985. Artichokes were fertilized four times a year. Figure 4 shows the row crop rotation schedule for the 5 years of the MWRSA. Fertilization regimes varied with each crop's requirements, but all row crops received an application of fertilizer before planting.

As with the demonstration field, local farming practices were followed throughout the project. A long-time local farming enterprise provided operational guidance, assistance, and farm labor. Standard agricultural practices for artichokes were followed, including trapping and poisoning gophers, baiting field mice, spraying pesticides or pheromones every 2 or 3 weeks, irrigating about six times per season, field cultivation, fertilizing four times each season, harvesting about every 2 weeks, cutting back plants in late spring, and periodically cutting dead stalks. Row crops were grown using standard agricultural practices including sprinkler and furrow irrigation, fertilization, and spraying with herbicides and pesticides.

Baseline Studies

Before the start of the 5-year MWRSA field demonstration, a number of baseline studies were carried out to ascertain the uniformity of the soil on the site of the experimental plots and to ensure the safety of downwind areas from windblown aerosols during irrigation with reclaimed wastewaters.

Data gathered in baseline studies not only helped select the site and configuration, but also formed a pre-experiment documentation of soil conditions for comparison with conditions at the end. Baseline studies of aerosols generated by spray irrigation were conducted to ensure the safety of farm workers and local residents. It was determined that the risk was extremely low for properly treated reclaimed water.[4]

Analyses and Sampling Methods

The standard set of analytical parameters included 9 metals (cadmium, zinc, iron, manganese, copper, nickel, cobalt, chromium, and lead); 15 chemical parameters (pH, electrical con-

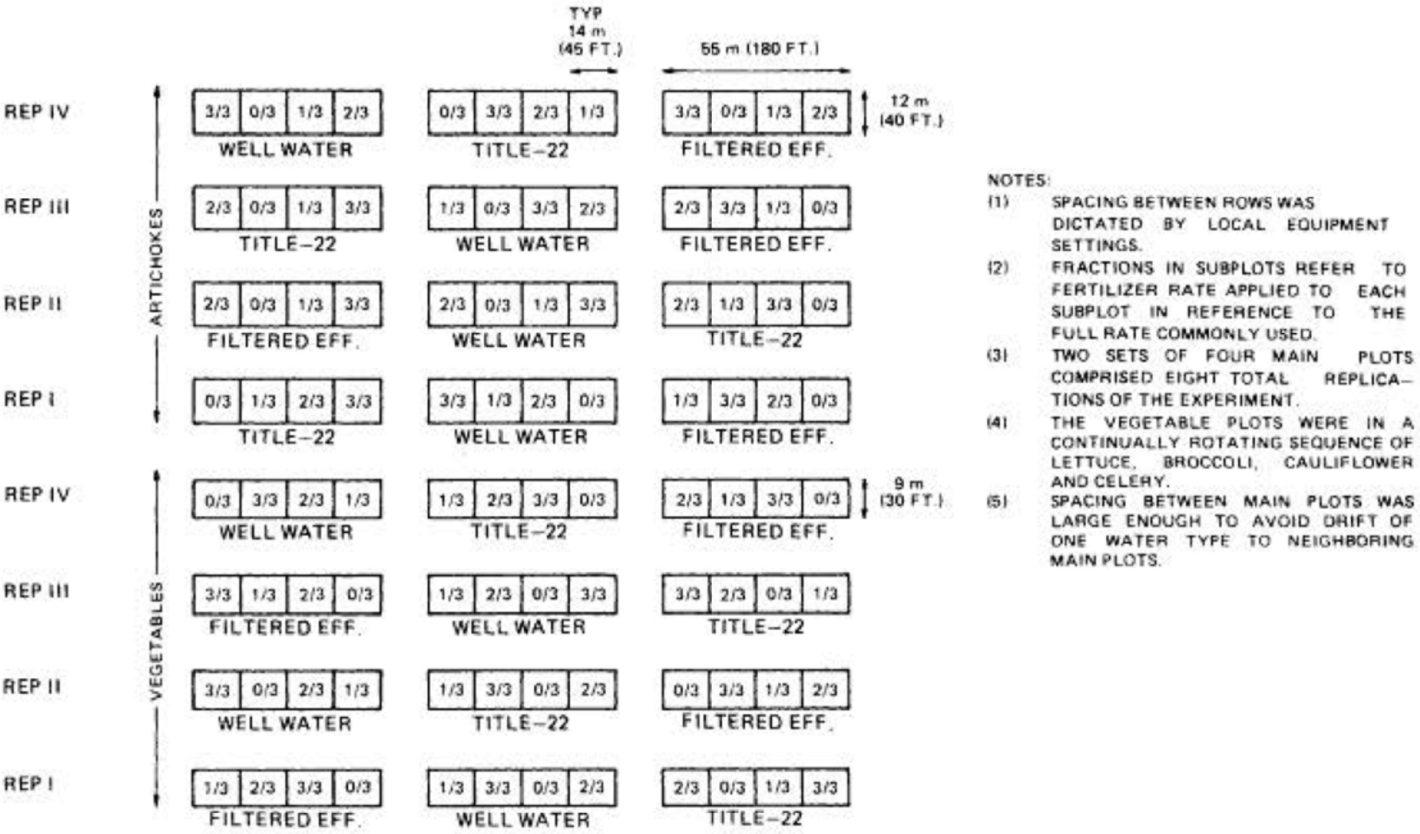

Figure 3—Layout of experimental plots with randomly assigned irrigation water type and fertilization rate.

ductivity, calcium, magnesium, sodium, potassium, carbonate, bicarbonate, total Kjeldahl nitrogen, nitrate nitrogen, ammonia nitrogen, phosphorus, chloride, sulfate, and boron); and 7 pathogenic indicators (total coliform, fecal coliform, salmonellae, shigellae, *Ascaris lumbricoides*, *Entamoeba histolytica*, and miscellaneous parasites).

Irrigation waters. Composite samples of the three irrigation waters were taken over a 3- to 5-day period at each irrigation event. The composite samples were divided into subsamples for metal and chemical analysis. In addition to the analyses described above, waters were analyzed for total dissolved solids, and methylene-blue-active substances. Sodium adsorption ratios (SAR) were also calculated. Grab samples were collected for pathogenic microorganisms and biochemical oxygen demand (BOD) analyses.

Soils. Soil samples from the experimental plots were collected from three depths: 30, 100, and 200 cm. These samples were analyzed for heavy metals, chemicals, and physical properties. Surface soils were sampled for microbiological content, which included analyses for total and fecal coliforms. Any samples with fecal coliform counts above the detection limit were tested for the presence of the pathogens salmonellae and shigellae. All soils were analyzed for parasites—*Ascaris lumbriocoides*, *Entamoeba histolytica*, and other miscellaneous parasites.

The 15 chemical parameters and 9 heavy metals were analyzed in all soil samples at three depths. In addition, SAR and adjusted SAR values were calculated on the soil saturation extracts.

Plant tissues. The same nine metals were also investigated in samples of the edible tissues of plants collected at harvest at each of the 96 subplots. The residual tissue of all vegetables grown was also sampled at the same frequency and analyzed for cadmium, zinc, and boron. The main purpose of these analyses was to assess the potential for bioaccumulation through the food chain, should residues be used as feed for cattle or other livestock. Both edible and residual tissues were sampled and analyzed for bacteriological indicators and parasites.

Samples of edible tissues were also taken from neighboring and nearby artichoke fields at distances of 15, 30, 60, 150, 300 and 1000 m for pathogen and metals assays. Sample harvests of all crops were taken from the central portions of plots. Crops and harvests were monitored to detect qualitative differences attributable to the different irrigation waters.

Results

Analysis of variance (ANOVA)[5] was the primary statistical technique used to determine if significant differences could be detected between the characteristics of the soils and plants receiving different water types and fertilization rates.

Irrigation waters. *Chemical constituents.* Table 3 shows chemical characteristics of irrigation waters used in the experimental fields. As expected, the two treatment effluents had relatively higher levels of most constituents than did well water. Levels of nutrients and salts in the irrigation waters are of particular concern. The nutrient concentrations, nitrogen, phosphorus, and potassium were consistently lowest in well water. In nearly all cases, the FE water had the highest concentration

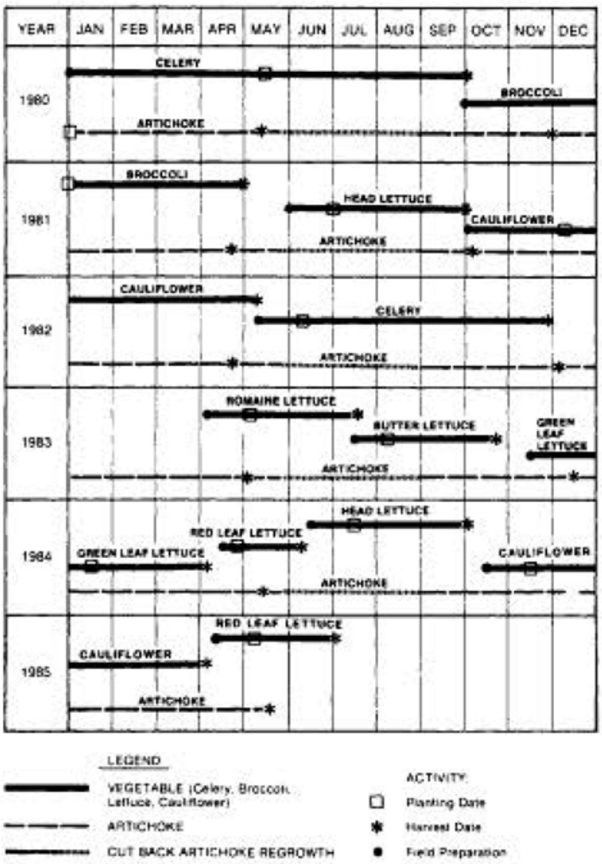

Figure 4—Crop rotation schedule for the 5-year MWRSA pilot study.

of nutrients, containing substantially more inorganic nitrogen and phosphorus than the T-22 water. Salinity and levels of sodium (sodicity) were also higher in the two effluents than in well water.

Heavy metals. Table 4 presents range and median values of metals in irrigation waters. Levels of metals in irrigation waters were often below detection limits in all three water types. This is the reason why ranges of concentrations are presented in Table 4.

Bacteria and parasites. During the 5 years of this study, the quality of both reclaimed waters improved because of the continued improvement in treatment plant operations and reclaimed water storage procedures. All three types of waters, including the well water control, periodically exhibited high total coliform levels. Both the FE and T-22 processes were capable of producing reclaimed water that meets the most stringent California Wastewater Reclamation Criteria. Fecal coliform levels in all three water types were at or below 2.2 MPN/100 mL most of the time. No salmonellae, shigellae, *Ascaris lumbricoides, Entamoeba histolytica,* or other parasites were ever detected in any of the irrigation waters.

Suitability of waters for irrigation. *Chemical constituents.* The adjusted SAR, as defined in the Table 3 footnote, is a measure of the probable influence the sodium ion has on soil properties. Increasing sodium in the soil can affect soil structure, infiltration, and permeability. A high percentage of exchangeable sodium in the soil can cause conditions that are unfavorable for water movement and plant growth. For the specific soil at the MWRSA project site (a 50% montmorillonite and 50% illite-vermiculite clay mixture), an adjusted SAR of 7 or less is considered to pose no problem; 7 to 12 would cause increasing problems; and greater than 12 would potentially pose a severe problem.

Well water consistently exhibited adjusted SAR values of less than 4, which is below the problem threshold. Adjusted SAR values for T-22 process water were generally within the range of increasing potential problems (7 to 12). For the FE process, values were generally in the range of increasing potential problems with a few values reaching the range of severe problems (above 12). The difference between the adjusted SAR values for the T-22 water and the FE water is probably due to the lower alkalinity in the T-22 water caused by the higher doses of alum added during treatment. The relationship between the adjusted SAR of the three water types as measured at each irrigation event and total dissolved solids (TDS) is shown in Figure 5. Irrigation water with relatively high sodium and low total salt content may result in poor soil physical conditions. Figure 5 shows the boundary between favorable and unfavorable conditions for irrigation waters which was developed by Oster and Rhoades.[6] Although adjusted SAR values of the two treatment effluents are much higher than those observed in either well water or water from the nearby Salinas River, the salinity of the reclaimed water (measured as TDS) is correspondingly high. This generally puts the reclaimed water in the favorable water quality range for irrigation with regard to soil permeability.[6-8]

High levels of salinity may additionally affect plant growth through osmotic relationships or specific ion toxicity. In well water samples, levels of TDS were consistently less than 480 mg/L (the problem threshold for irrigation waters). In the T-22 and FE waters it generally varied between 800 and 1000 mg/L (in the range of increasing potential problems). None of the irrigation waters had TDS values greater than 1900 mg/L (the severe problem range).

Heavy metals. From the perspective of heavy metal content, both types of reclaimed water were highly suitable for irrigation water, containing very low levels of metals. Overall, levels of metals provided by the two effluents were an order of magnitude lower than the metal input from impurities in commercial fertilizers.

Bacteria and parasites. Levels of bacteria were lower than levels typical of many surface waters. Fecal coliform levels from 700 to 12 000 MPN/100 mL have been reported from irrigation waters in the western U. S.[9]

Soils. *Chemical parameters.* Statistically significant differences between the soils irrigated with the three water types were found in many chemical parameters. In nearly all cases the relative values of the concentrations found in the soils followed the same relative value relationships found in the irrigation waters. Concentrations were generally highest in the FE-irrigated soil samples, and lowest in the well water-irrigated soil samples. In many instances increased fertilizer application rates were found to have effects on concentrations of various soil chemical parameters, similar to that of effluent irrigation. The following parameters increased significantly with higher fertilizer rates for more than half of the sampling events: electrical conductivity, calcium, magnesium, sodium, potassium, nitrate, and sulfate. Reclaimed water irrigation also produced higher soil concentrations of these

Table 3—Chemical characteristics of irrigation waters used in the experimental fields (in mg/L unless otherwise noted).

Parameter	Well water		Title-22 water		Filtered effluent	
	Range	Median	Range	Median	Range	Median
pH[a]	6.9–8.1	7.8	6.6–8.0	7.2	6.8–7.9	7.3
Electrical conductivity[b]	400–1344	700	517–2452	1256	484–2650	1400
Calcium	18–71	48	17–61.1	52	21–66.8	53
Magnesium	12.6–36	18.8	16.2–40	20.9	13.2–57	22
Sodium	29.5–75.3	60	77.5–415	166	82.5–526	192
Potassium	1.6–5.2	2.8	5.4–26.3	15.2	13–31.2	18
Carbonate, as $CaCO_3$	0.0–0.0	0.0	0.0–0.0	0.0	0.0–0.0	0.0
Bicarbonate, as $CaCO_3$	136–316	167	56.1–248	159	129–337	199.5
Hardness, as $CaCO_3$	154–246	202.5	187–416	217.5	171–435	226.5
Nitrate as N	0.085–0.64	0.44	0.18–61.55	8.0	0.08–20.6	6.5
Ammonia as N	ND[e]–1.04	—	0.02–30.8	1.2	0.02–32.7	4.3
Total phosphorus	ND–0.6	0.02	0.2–6.11	2.7	3.8–14.6	8.0
Chloride	52.2–140	104.4	145.7–7.841	221.1	145.7–620	249.5
Sulfate	6.4–55	16.1	30–256	107	55–216.7	84.8
Boron	ND–9	0.08	ND–0.81	0.36	0.11–0.9	0.4
Total dissolved solids	244–570	413	643–1547	778	611–1621	842
Biochemical oxygen demand (BOD)	ND–33	1.35	ND–102	13.9	ND–315	19
Adjusted SAR[c]	1.5–4.2	3.1	3.1–18.7	8.0	3.9–24.5	9.9
MBAS[d]	—	—	0.095–0.25	0.136	0.05–0.585	0.15

[a] Standard pH units.

[b] Decisiemens per meter (ds/m).

[c] Adjusted sodium adsorption ratio:[7,8] adj. SAR = $\frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}[1 + (8.4 - pH_c)]$

[d] Methylene-blue active substance (MBAS).

[e] ND = Chemical concentration below detection limit. Detection limits are as follows: NH_3-N = 0.02 mg/L; P = 0.01 mg/L; B = 0.02 mg/L; BOD = 1 mg/L; and MBAS = 0.05 mg/L.

parameters, except potassium. It also increased the SARs and the levels of chloride in the soil extract.

Although many statistically significant differences were found, none of the data indicated that the soils irrigated with any of the three water types were being adversely affected. Irrigating with reclaimed water did not have any harmful effects on the soil.

Heavy metals. The most significant result of the soil analyses for heavy metals was the finding that fertilizer rates were responsible for a great deal of variation in metal concentrations, while water types had no measurable effect. None of the nine heavy metals studied (cadmium, zinc, iron, manganese, copper, nickel, cobalt, chromium, or lead) manifested any consistently significant differences in concentration among plots irrigated with the different water types. Furthermore, except in the case of copper, no increasing trends in metal concentrations with time over the 5 years were observed. The gradual increase observed for copper occurred equally for all water types. At the end of the 5 years, copper concentrations were still below the average for California soils. As shown in Table 4 the concentrations of these metals in all three types of irrigation water were so low (below detection level for the most part) that calculation of the theoretical input and accumulation would lead one to expect no significant accumulation or difference over the 5-year period. For much longer periods, the same calculations would lead to the same conclusions for all metals except possibly iron and zinc (two essential plant and animal micronutrients). Iron was generally measured at higher concentrations in the well water than in either reclaimed water. Zinc, however, was higher in both types of reclaimed water than in well water, although the actual concentrations were on the order of 0.1 mg/L in the two reclaimed waters. At these levels, uptake by plants would be faster than accumulation from irrigation input.

Input of zinc and other heavy metals from commercial chemical fertilizer impurities is far greater than from reclaimed water, and accounts for the large concentration differences observed at the three soil depths sampled throughout the 5 years. These differences have resulted from many decades of continuous farming with regular application of fertilizers. Levels of manganese, cobalt, nickel, and boron were seen to increase significantly with increased fertilization at over half of the sampling events.

Table 5 summarizes the 5-year results of all the heavy metals analyses of soils in the artichoke plots. Each number in Table 5 is the average of 480 to 640 individual field samples, and this only represents half the test plots. Values for each water type are averaged over all fertilizer rates. Likewise, values for each fertilizer rate are averaged over all three water types. The other half of the plots, planted a succession of annual vegetables (lettuce, broccoli, cauliflower, and celery), produced similar results.

Bacteria and parasites. The levels of total and fecal coliform

Table 4—Heavy metal concentrations (in mg/L) in irrigation waters.

Parameter	Well water		Title-22 water		Filtered effluent		Irrigation water criteria[a] (continuous)	Drinking water regulations
	Range	Median	Range	Median	Range	Median		
Cadmium	ND–0.1	ND	ND–0.1	ND	ND–0.1	ND	0.010	0.010[b]
Zinc	ND–0.6	0.02	0.07–6.2	0.33	ND–2.06	0.195	2.0	5[c]
Iron	ND–0.66	0.1	ND–2.3	0.05	ND–0.25	0.06	5.0	0.3[c]
Manganese	ND–0.07	ND[d]	ND–0.11	0.05	ND–0.11	0.05	0.20	0.05[c]
Copper	ND–0.05	0.02	ND–0.05	ND	ND–0.04	ND	0.20	1[c]
Nickel	0.001–0.200	0.04	0.002–0.180	0.04	0.004–0.200	0.04	0.20	—
Cobalt	ND–0.057	ND	0.001–0.062	0.002	ND–0.115	0.05	0.050	—
Chromium	ND–0.055	ND	ND	ND	ND	ND	0.10	0.05[b]
Lead	ND	ND	ND	ND	0.001–0.700	0.023	5.0	0.05[b]

[a] Water Quality Criteria 1972; Ecological Research Series, U. S. EPA.

[b] Primary Drinking Water Regulations (metals that post a potential adverse health effect), U. S. EPA.

[c] Secondary Drinking Water Regulations (metals that post an aesthetic problem), U. S. EPA.

[d] ND = Metal concentration below detection limit. Detection limits were improved during the 5-year period and were as follows (in mg/L):

Element	Year 1	Years 2 and 3	Years 4 and 5
Cd	0.1	0.001	0.001
Zn	0.5	0.02	0.02
Fe	0.03	0.03	0.03
Mn	0.05	0.05	0.05
Cu	0.02	0.02	0.001
Ni	0.2	0.05	0.001
Co	0.1	0.05	0.001
Cr	0.2	0.04	0.04
Pb	0.2	0.05	0.001

in soils irrigated with the two types of reclaimed water were similar to levels in well water-irrigated soils. No parasites were ever detected in soil samples.

Plant tissues. *Heavy metals.* No consistently significant difference in heavy metal concentrations in plant tissues was observed between plants irrigated with reclaimed waters and with well water in 16 samplings over the 5-year field trials. In addition, metal content of artichoke tissues from neighboring fields showed no relationship to distance from the site of the plots.

Analysis of residual tissues produced results similar to those from edible tissues, that is, no consistently significant difference was observed between plants irrigated with well water and with either of the two reclaimed waters. However, consistent differences in the accumulation of zinc and cadmium were observed between edible and residual tissues (higher cadmium in residual tissues and higher zinc in edible tissues for all vegetables studied).

Bacteria and parasites. The levels of total and fecal coliform in plant tissue irrigated with all three types of water were generally comparable. No consistently significant difference attributable to water type was observed. Parasites were detected in plant tissue only in Year 1, and there were no differences in the level of contamination between reclaimed water- and well water-irrigated crops.

Sampling of plants from neighboring fields detected no relationship between bacteriological levels and the distance from the field site. The aerosol transmission of bacteria was thus deemed unlikely.

Crop yields. Statistically significant yield differences due to water type were observed in the celery and broccoli crops. In both cases, yields were significantly higher in the crops irrigated with the reclaimed waters. The FE-irrigated crop yields were usually slightly higher than the T-22-irrigated crop yields. Yields of lettuce and celery showed an interaction of water type and fertilization; reclaimed water irrigation improved yields in un-

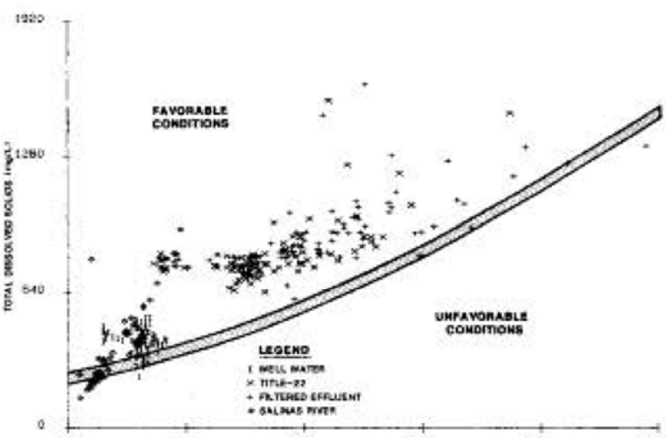

Figure 5—Relationship between adjusted SAR and TDS for four different irrigation waters.

Table 5—Average concentration of heavy metals in soil profile of artichoke plots (in mg metal/kg soil).

Heavy metal	Soil depth, cm	Water type[a]			Fertilizer rate[b]				Average
		WW	T-22	FE	0	33%	66%	100%	
Cadmium	30	0.46	0.44	0.45	0.43	0.44	0.46	0.45	0.45
	100	0.16	0.16	0.13	0.16	0.16	0.14	0.13	0.14
	200	0.13	0.08	0.10	0.12	0.10	0.11	0.09	0.10
Zinc	30	1.41	1.33	1.53	1.37	1.46	1.42	1.45	1.42
	100	0.33	0.36	0.34	0.35	0.35	0.35	0.33	0.34
	200	0.50	0.40	0.47	0.49	0.48	0.44	0.42	0.45
Iron	30	49.68	41.48	45.73	39.66	43.81	47.73	51.31	45.63
	100	8.19	8.13	6.07	7.59	7.82	7.44	7.00	7.47
	200	12.59	7.79	7.65	9.61	9.72	8.98	9.08	9.35
Manganese	30	23.30	20.21	24.53	16.01	18.64	24.18	31.86	22.67
	100	4.94	4.71	4.19	4.63	4.89	4.45	4.48	4.61
	200	6.26	4.63	5.04	5.87	5.13	5.33	4.90	5.31
Copper	30	2.06	2.02	2.09	2.05	1.97	2.11	2.11	2.06
	100	1.57	1.84	1.40	1.60	1.73	1.43	1.65	1.60
	200	1.79	1.25	1.51	1.68	1.55	1.41	1.41	1.52
Nickel	30	6.88	6.38	6.81	6.19	6.51	6.92	7.15	6.69
	100	0.91	0.93	0.69	0.92	0.85	0.83	0.78	0.84
	200	0.63	0.39	0.47	0.58	0.47	0.50	0.42	0.49
Cobalt	30	0.16	0.16	0.18	0.13	0.14	0.18	0.22	0.17
	100	0.09	0.09	0.09	0.09	0.09	0.10	0.09	0.09
	200	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Chromium	30	0.15	0.13	0.15	0.14	0.14	0.14	0.15	0.14
	100	0.10	0.10	0.10	0.09	0.10	0.11	0.10	0.10
	200	0.10	0.09	0.10	0.09	0.10	0.09	0.09	0.10
Lead	30	0.98	0.92	0.96	0.97	0.94	0.93	0.98	0.95
	100	0.64	0.71	0.54	0.66	0.65	0.56	0.63	0.63
	200	0.70	0.49	0.60	0.66	0.62	0.56	0.54	0.59

[a] Averaged for all fertilizer rates.
[b] Averaged for all water types.

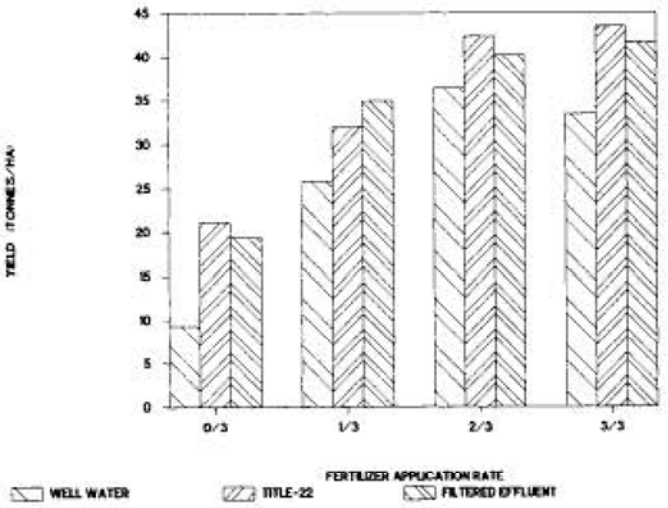

Figure 6—Mean lettuce yield as a function of fertilizer rate and water type.

fertilized plots but had little or no effect on yields of plots receiving fertilizer. Artichoke yields were similar for all three water types. Yields of all five crops leveled off at or below 66% the standard local fertilization application rate. Use of the full (100%) local fertilization rate did not further improve yields. Thus, reductions, by up to 30% in fertilizer applications may be possible for all of the crops. Figure 6 depicts yields of lettuce by water type and fertilization rate.

Quality and shelf life. Field inspection of crops showed no leaf damage from residual chlorine in the effluents, and no differences in appearance or vigor of plants irrigated with different water types. Samples of each crop harvested were boxed and placed in cold storage warehouses for varying time periods of up to 4 weeks following harvest. The produce was examined at weekly intervals during the storage period for signs of pithiness, flaccidity, black heart, outside tissue breakdown, discoloration, decay, and other signs of spoilage. In general, all of the produce was of excellent quality and showed no unexpected deterioration over time. The quality and shelf life of all produce grown with the two reclaimed waters was as good as, and in some instances superior to, the produce grown with well water.

Summary of the MWRSA Project and Discussions

The information obtained through 5 years of the MWRSA field operation can best be discussed in terms of its significance to the four categories of people that would be affected by full-scale wastewater reclamation and reuse for food crop irrigation. These are the regulatory agencies; the farmers; the shippers, buyers, and consumers of food crops; and the agency that provides the reclaimed water.

Regulatory agencies. The regulatory agencies that were involved with the MWRSA, and will have jurisdiction over the full-scale use of reclaimed water in Monterey County, are the California State and County Health Departments, the State Department of Water Resources, the State Department of Food and Agriculture, the State Water Resources Control Board, and the Regional Water Quality Control Board. They are concerned mainly with the health and water pollution control aspects of the wastewater reclamation and reuse practices. The data obtained show that even though coliform bacteria are often present (as a result of regrowth in storage) in the reclaimed water, no viruses or other pathogens have been found.

Virus inoculation of plants being grown in the field and in an environmental chamber at the Sanitary Engineering and Environmental Health Laboratory at the University of California, Berkeley, has also shown that naturally occurring environmental conditions will cause a rapid die-off of viruses. This provides an additional safety factor against virus transmission through produce consumption. Virus seeding test reports in the MWRSA—Final Report[1] have verified that the analytical techniques used are capable of detecting viruses if they are, in fact, present. Coliform density found on the surfaces of plants was found to be unrelated to irrigation with reclaimed water. Heavy metal levels in the reclaimed waters have been consistently below the criteria levels applicable to both agricultural irrigation and drinking water. Heavy metals were not found to be accumulating to any significant levels in either the harvested vegetables or the soils. Heavy metal levels were influenced more by fertilizer application than by the irrigation water.

No project-related health problems were detected through medical examinations and the serum banking program routinely conducted for the project personnel. Sampling of aerosols, as well as sampling of plants from nearby fields, showed no buildup of heavy metals or any other type of potentially harmful effect from the use of reclaimed water for crop irrigation. No restrictions with regard to the method of irrigation (spray, flood, and so on), cultivation or harvesting techniques have been employed, nor have any been found to be necessary.

Impacts on groundwater quality resulting from irrigation with reclaimed water were also studied. Analyses at the end of the project did not show any detectable changes in groundwater quality.

From the perspective of the regulatory agencies involved with wastewater reclamation and reuse, the MWRSA has demonstrated that the use of reclaimed water for irrigation of food crops that are eaten raw does not pose any health-related problems after the specified wastewater treatment trains are used.

Farmers. A number of agriculturalists from northern Monterey County were represented on the MWRSA Task Force which guided the scope and activities of the project. Included in this group were farmers, farm advisors, food processors, and grower-shipper association representatives. The land that was farmed in the MWRSA was leased from one of these farmers. This farmer also contracted with the MRWPCA to perform most of the routine cultural practices using regular farming equipment and personnel. Because of its vital interest in the potential for wastewater reclamation, the local agricultural community was quite active in the conduct of the MWRSA. Their main areas of interest were the quality and yield of the crops being irrigated with reclaimed water, any special farming practices that might be required for farming with reclaimed water, and any special considerations that could affect the marketability or consumer acceptance of such crops.

The quality and yield of all six crops irrigated with the two reclaimed waters were equal to or greater than those of the crops grown with well water. The appearance and shelf-life longevity of the crops produced using reclaimed water were similar to those produced using well water.

The demonstration plots, which were farmed for the first 2 years of the MWRSA, successfully demonstrated that conventional farming practices were also suitable for cultivating and harvesting crops irrigated with reclaimed water. No restrictions on farm worker exposure to the reclaimed water, crops, or soil were found necessary. Routine plant tissue analyses showed no levels of any constituents contributed by the irrigation water that would be harmful to proper plant growth. These findings demonstrate that there would be no adverse economic impacts on crop production associated with using reclaimed water for irrigation of vegetables.

Farmers have been interested in the potential long-term effects on the soils and underlying groundwater quality resulting from the use of reclaimed water. At the conclusion of the 5-year pilot project no soil or groundwater problems are anticipated resulting from long-term, full-scale use of reclaimed municipal wastewater.

Shippers, buyers, and consumers. The shippers, buyers, and consumers of produce grown with reclaimed water are concerned with some of the same issues of concern to the regulatory agencies and the farmers. These issues include the health and safety aspects of the produce, its quality and appearance, and its cost. As discussed above, no drawbacks were discovered in any of these categories resulting from the use of reclaimed water for the irrigation of food crops. No adverse health effects were found, and the quality and appearance of the produce were excellent. No factors which would result in higher crop production costs due to the use of reclaimed water for irrigation were identified.

As part of the project, a special study was performed by a San Francisco-based marketing research firm on the subject of the marketability of food crops grown with reclaimed water. One key issue investigated was whether produce grown with reclaimed water would be required to be labeled to identify this fact. The conclusion was that there was no regulatory requirement to label or separate produce grown using reclaimed water. Further, it was reported that buyers, shippers, and other "intermediaries" would readily accept such produce as long as the regulatory agencies approved the use of reclaimed water. The intermediaries actually preferred that the produce not be labeled, as labeling adds an additional step in the handling and distribution of the produce. The marketing firm also investigated the potential for negative rumors (either spontaneously or intentionally generated) to be circulated that could adversely affect produce sales. It was concluded that the risks to growers from such rumors were extremely low, because rumors regarding produce are rare and would be unlikely, based on historical precedent. In addition, rumors can readily be contained or dispelled by dissemination of factual information.

The wastewater reclamation agency. The entity producing and delivering reclaimed water is concerned mainly with producing a safe water that is approved by all regulatory agencies for crop irrigation, and is purchased by the local farmers. The agency that provides the reclaimed water thus shares all concerns described above, because the attitudes of the people in each of the above categories will have a direct influence on the market for reclaimed water. Acceptance by the regulatory agencies, positive conclusions from the marketing consultant, and personal observations and participation in the project by local farmers are the keys to developing a sound market for the reclaimed water. As discussed above, potential users of the reclaimed water were satisfied that the regulatory agencies were approving the use of reclaimed water, and they encountered no farming problems with its use.

Cost and feasibility. At the conclusion of the MWRSA project, estimates were made of the cost of reclaimed water. Capital and operations and maintenance (O&M) cost estimates for full-scale regional reclamation were based on the design criteria presented in the MWRSA—Final Report.[1] The present worth of 20 years of operation was estimated for each of the three water reclamation plant alternatives: Title-22, filtered effluent, and filtered effluent with flocculation. The evaluation assumed that the water reclamation plant would operate at full capacity during the entire irrigation season, an average of 250 d/a. It also assumed that the reclamation plant would be a 114×10^3-m^3/d facility with capital costs amortized at a discount rate of 9%. Operations costs included labor, maintenance, energy, chemicals, administration, and incremental sludge handling and disposal.

The estimated cost of reclaimed water produced by each of these three process alternatives was determined and is presented in Table 6. The unit cost of producing reclaimed water was determined by dividing the amortized capital cost of reclamation facilities plus the annual O&M cost by the amount of water estimated to be reclaimed during each year.

The value of the nutrients provided by each type of reclaimed water was estimated at about $0.02/$m^3$. However, it should be noted that the fertilizer value of reclaimed water may not be fully realized by the growers, especially in the initial years. In addition water may be distributed as a blend of reclaimed water with imported fresh water from impoundments.

Irrigation with reclaimed water is not expected to involve any additional costs to the grower due to its water quality. Any SAR problems that might be expected would be of a long-term nature (probably over 50 years) and could be remedied with simple lime or gypsum application. The annual costs of such treatment would be relatively insignificant.

Implementation of water reclamation and reuse. It is planned that wastewater reuse in northern Monterey County will be undertaken in conjunction with the plans of the Monterey County Flood Control and Water Conservation District (MCFCWCD) for supplying Salinas River water to the Castroville farming areas. The reason for this joint development is that a piped distribution system is contemplated in the MCFCWCD scheme, which is aimed at stopping seawater intrusion into the coastal aquifers. This distribution system could also serve to distribute reclaimed water, blended with the imported surface water, to the points of use. The above scheme, known as the Castroville Irrigation Project, would supply about 39×10^6 m^3/a. Of this total amount, reclaimed wastewater could supply approximately 28×10^6 m^3/a.

Table 6—Estimated costs[a] of reclaimed water for various tertiary treatment processes.

Treatment process	Estimated cost
Filtered effluent	$0.05/$m^3$
Filtered effluent with flocculation	$0.06/$m^3$
Title 22 with 50 mg/L alum	$0.09/$m^3$
Title 22 with 200 mg/L alum	$0.13/$m^3$

[a] Assumptions: Plant design flow of 114×10^3 m^3/d; 28 mil m^3/a of reclaimed water will be delivered for irrigation; and for FE-F process, estimated capital cost is $11 170 000 and estimated annual O&M cost is $376 000.

Conclusions

The results obtained from the 5-year MWRSA indicate that the use of reclaimed water for food crop irrigation is safe and acceptable. No drawbacks in terms of soil or groundwater quality degradation were observed. Conventional farming practices were shown to be adequate, and the marketability of the produce did not appear to pose any obstacles.

Irrigation with highly treated municipal wastewater produced excellent yields of high-quality produce. Cauliflower and broccoli yields were significantly improved by irrigation with reclaimed water.

No problem was observed with the accumulation of heavy metals in the crops or the soil due to reclaimed water use. In fact, the conventional use of fertilizers was found to add far greater quantities of heavy metals. Chlorine residuals, varying over a wide range in the reclaimed water, had no observable effect on crops. Hence, dechlorination is not necessary or desirable.

With regard to salinity and levels of sodium, reclaimed water generally fell within the favorable range for irrigation. In general, a high SAR is only a problem if overall salinity is low. Higher SAR values in reclaimed water from the T-22 and FE processes were offset by the correspondingly higher levels of TDS. During the course of the study, reductions in permeability of reclaimed water-irrigated soils were not observed. The MWRSA has successfully proved the acceptability of irrigating food crops with reclaimed water from the standpoints of regulatory agencies, farmers, consumers, and wastewater treatment agencies.

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