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Irrigation with Reclaimed Municipal Wastewater - A Guidance Manual

Edited by
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IRRIGATION WITH RECLAIMED MUNICIPAL WASTEWATER —A GUIDANCE MANUAL

Prepared by

Department of Land, Air and Water Resources
University of California, Davis

For

CALIFORNIA STATE WATER RESOURCES CONTROL BOARD

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PREFACE

Irrigation with Reclaimed Municipal Wastewater—A Guidance Manual is for use in the planning, design, and operation of agricultural and landscape irrigation systems using reclaimed municipal wastewater. It is written for civil and sanitary engineers, agricultural engineers, and agricultural extension workers and consultants. The manual is also useful as a reference for public works officials, municipal wastewater treatment plant operators, and students at colleges and universities. Several chapters were written specifically for California readers, but much of the *Guidance Manual* is applicable to arid and semi-arid environments outside of California.

The emphasis in this manual is on the beneficial use of reclaimed wastewater for agricultural and landscape irrigation. In this respect, it differs from publications such as the U.S. Environmental Protection Agency's *Process Design Manual—Land Treatment of Municipal Wastewater.* For example, the *Guidance Manual* emphasizes irrigation for the purpose of optimizing crop production; therefore, it includes detailed instruction in the calculation of crop water requirements. Furthermore, the benefits and limitations of using reclaimed municipal wastewater for agricultural and landscape irrigation are discussed, as are other topics of special interest, including water management for salinity and sodicity control, and economic and legal aspects of reclaimed wastewater irrigation.

This *Guidance Manual* is a result of the cooperative effort among the University of California, the California State Water Resources Control Board, and other agencies and consultants, and represents the collective effort of 27 authors and several staff members over a period of two and a half years. The *Guidance Manual* has been reviewed by the peer reviewers whose names appear in the acknowledgment section of the Manual.

G. Stuart Pettygrove — Takashi Asano
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CHAPTER 1

INTRODUCTION: CALIFORNIA'S RECLAIMED MUNICIPAL WASTEWATER RESOURCE

G. Stuart Pettygrove, David C. Davenport, and Takashi Asano

Much of California is semiarid. It not only has a poor geographic and seasonal distribution of water, but also faces increasing competitive demands for that water. Ironically, although the state's fresh water resources are abundant, not all of them are available to meet agricultural, municipal, industrial, environmental, and instream demands. Furthermore, much of the water demand occurs in areas where rainfall and local supplies are insufficient, thereby requiring importation of fresh water and wastewater reuse.

Some of the water that is reused includes treated municipal wastewater which must be applied in accordance with increasingly stringent regulations. Efforts should be continued to gainfully use this resource by irrigating selected agricultural and landscape vegetation and by supplementing freshwater supplies through return flows to streams and groundwater.

WASTEWATER REUSE AS PART OF CALIFORNIA'S WATER BALANCE

California's annual water balance depends on the difference between annual water inflow (mainly precipitation) and annual water outflow (irrecoverable losses, roughly two-thirds to the atmosphere and one-third to the ocean). Any water conservation action that reduces these irrecoverable losses will improve the temporal and spatial availability of water for additional beneficial uses during the year. Water is conserved within the state when potentially recoverable waters, such as return flows from agricultural and urban areas, are indeed recovered and reused. Such reuse supplements local fresh water supplies which are subject to increasing competitive demands. However, unless the wastewater would otherwise be irrecoverably lost (e.g., outflow to the ocean from coastal cities or unproductive evapotranspiration from inland areas), wastewater reclamation and reuse does not increase the state's net quantity of water available for additional uses. Substitution of reclaimed wastewater for pumped fresh water does, however, result in local water savings. In addition, wastewater reclamation has many other potential benefits including: (1) reduced costs of wastewater treatment and disposal, (2) reduction of pollutants in receiving water by diverting treated wastewater to land, and (3) delay, reduction, or elimination of fresh water facilities, thus reducing impacts on natural water courses and reducing water supply costs.

The total annual quantity of water applied for agricultural, urban, and other uses in California is about 42.2 million acre-feet (MAF), most of which (35.6 MAF) is for agriculture [1]. Approximately 5.8 MAF is applied annually for urban use, of which 2.4 MAF goes to evapotranspiration and deep percolation, leaving 3.4 MAF as the average amount of urban wastewater generated annually.

Table 1-1 shows the disposition of California's 3.40 MAF of municipal wastewater. About 2.54 MAF is irrecoverably lost from the state because it is discharged to saline waters, mainly the ocean (2.44 MAF), or evaporates (0.10 MAF), leaving only 0.86 MAF of municipal wastewaters actually reused. Of this 0.86 MAF, 0.25 is classified as intentional or planned, and 0.61 as incidental, reclamation (see footnotes to Table 1-1). Thus, although 18% of the 3.4 MAF of generated municipal wastewater is treated and returns to the state's freshwater system for subsequent incidental use, only 7% is put to "intentional" use.

CURRENT USE OF TREATED MUNICIPAL WASTEWATER

Land application of municipal wastewater is a well-established practice in California. According to a California State Department of Health Services (DOHS) survey [2], in 1977 wastewater was reclaimed at over 200 treatment plants and was applied to more than 360 locations (Table 1-2). Much of the reclaimed municipal wastewater (57%) was used for irrigation of fodder, fiber, and seed crops (a use not requiring a high degree of treatment), and only 7% was used for irrigation of orchard, vine, and other food crops. An important use (about 14%) was irrigation of golf courses, other turfgrass, and landscaped areas. Apart from irrigation use, the survey showed that 14% of reclaimed municipal wastewater was applied for groundwater recharge, 5% for industrial use, and smaller amounts were used for other purposes.

Table 1-1. Disposition of treated municipal wastewater in California, 1980 data [1].

	Volume	
	million acre-ft/year	%
Discharge to saline water	2.44	72
Evaporation and evapotranspiration	0.10	3
Intentional use of reclaimed wastewater[a]	0.25	7
Incidental use of treated wastewater[b]	0.61	18
Total municipal wastewater	3.40	100

a. Intentional - planned use of treated effluent that would otherwise be discharged without being put to direct use.

b. Incidental - use of treated effluent after it is discharged to the fresh water system, so that its subsequent use is unplanned and is merely incidental to wastewater treatment and disposal.

Table 1-2. Use of reclaimed municipal wastewater in California, 1977 data [2].

Type of reuse	Number of use areas	Volume acre-ft/yr	%
Irrigation			
Fodder, fiber, and seed crops	190	104,279	57
Landscape: golf courses, cemeteries, freeways[a]	77	21,175	12
Orchards and vineyards	21	8,066	4
Other food crops	8	4,974	3
Landscape: playgrounds, schoolyards, parks[a]	27	2,733	2
Groundwater recharge	5	25,981	14
Industrial uses	8	8,613	5
Non-restricted recreational impoundments	1	2,455	1
Wildlife habitat	1	621	<1
Construction and dust control	12	190	<1
Aquaculture	1	2	<1
Total	363	183,525	100

a. Landscape irrigation is divided into two categories because Wastewater Reclamation Criteria require that wastewater be treated to a higher degree for parks, schoolyards, etc. than for golf courses and low-public-contact types of landscaping (see Chapter 10 for details).

POTENTIAL FOR ADDITIONAL IRRIGATION WITH RECLAIMED MUNICIPAL WASTEWATER

The greatest potential for reclaimed municipal wastewater contributing to water supplies, i.e., to gaining "new" water for California, is in coastal regions or elsewhere where wastewater is currently lost from the fresh water system by discharge to the ocean or other saline bodies. The potential for increased intentional reclamation and reuse is also significant in the San Joaquin and Sacramento Valleys and adjacent foothills, but in those locations, new reclamation and reuse will not contribute significantly to the state's water balance.

So far, direct potable use of reclaimed wastewater, and to some extent groundwater recharge with reclaimed wastewater, have been discouraged by public health agencies. This reflects the concern that not enough is known about some reclaimed wastewater constituents -- chiefly stable trace-organic substances and viruses -- to allow such use on a large scale. Crop irrigation with reclaimed wastewater at proper application rates is viewed as a more conservative and acceptable approach.

Projected use of reclaimed wastewater to the year 2010 in California for all purposes is presented in Table 1-3. The potential reuse for irrigation in three parts of the state is described in the following sections.

Southern California Coastal Areas

Data in Table 1-3 indicate that 70% of the projected statewide increase in use of reclaimed municipal and industrial wastewater between 1980 and 2010 will take place in Southern California coastal areas. Turfgrass and other landscaping are the major users of irrigation water in those regions. Turfgrass and landscape are appropriate uses of reclaimed wastewater not only because of the large potential acreage, but because of the less-stringent treatment requirements for use on some categories of landscaping compared to requirements for use on food crops. Furthermore, many of the agricultural crops grown in the area are sensitive to salts found in some Southern California wastewaters. Since a high salt content in

Table 1-3. Present and projected annual use of reclaimed wastewater in California in 1,000's of acre-ft [1].

Hydrologic area	Year 1980	1990	2000	2010	Increase, 1980-2010
North Coast	9	10	10	10	1
San Francisco Bay	10	11	13	15	5
Central Coast	9	25	27	27	18
Los Angeles	59	101	196	267	208
Santa Ana	29	47	73	78	49
San Diego	9	43	55	55	46
Sacramento Basin	21	22	23	25	4
San Joaquin Basin[a]	23	25	29	33	10
Tulare Lake Basin[a]	67	78	86	99	32
North Lahontan	6	6	7	8	2
South Lahontan	4	13	15	15	11
Colorado River Basin	4	20[b]	33[b]	45[b]	41[b]
Total	250	401	567	677	427

a. Does not include planned reclamation of agricultural drainage water.

b. Includes reclaimed agricultural return flows (normally lost to the Salton Sea) for power plant cooling.

irrigation water reduces growth and yield, turfgrasses and woody landscape plant species (which are grown for ornamental purposes rather than yield) are appropriate species to irrigate with saline municipal wastewater effluents. Furthermore, many salt-tolerant species of landscaping plants and turfgrasses are available.

San Joaquin Valley Agricultural and Landscaped Areas

Overdraft of groundwater supplies, increasing energy costs for pumping, constraints on developing and transferring water from Northern California, and continued urban growth all point to a likely increase in the use of reclaimed wastewater in this area. For reasons explained above, wastewater reclamation and reuse in inland areas will not contribute "new" water to the state's water supply, but reclamation has many other potential benefits. Among these are energy savings, reduced cost of wastewater disposal, utilization of nutrients by crop and landscape plants, and delay, reduction, or elimination of construction of fresh water facilities. Wastewater supplies in the San Joaquin Valley are often geographically close to large acreages of fodder, fiber, and seed crops which do not require highly treated wastewater.

Sierra Foothill Agricultural and Landscaped Areas

Foothill areas draining into the Sacramento, San Joaquin, and Tulare Lake basins do not appear as separate areas in Table 1-3, but present a special opportunity for wastewater reclamation and reuse. An increase in the number of small-scale and part-time farmers and persons seeking a rural lifestyle in foothill areas is putting heavy pressure on limited water supplies. Wastewater reclamation and reuse in this environment may be less costly than treating to the degree necessary to eliminate pollution of surface waters. As in the San Joaquin Valley, irrigation with reclaimed wastewater will not usually represent new water to the state but may result in cost savings and environmental benefits.

USE OF THE GUIDANCE MANUAL

The main purpose of this manual is to assist planners and practicing engineers in understanding several aspects of the "field end" of reclaimed wastewater irrigation. Another objective is to encourage practices resulting in the economic maximum amount of harvested product (or in the case of landscaping, esthetic value) per unit of treated wastewater applied. The goal of maximum production is in contrast to the goal of wastewater disposal, but it does not conflict with the concept of slow-rate land treatment of wastewater as defined by the U.S. Environmental Protection Agency [3].

To meet these objectives, the manual presents a detailed treatment of special topics related to irrigation with reclaimed municipal wastewater rather than a "broad-brush" treatment of the entire field of irrigation system planning and design. The topics of special importance and the related chapters are summarized in the following sections.

Municipal Wastewater Characteristics and Suitability for Irrigation

One of the attractive features of irrigation with reclaimed wastewater, compared to several other non-potable and potable reuses, is that in many instances there is a less-stringent water quality requirement for irrigation, and hence a simpler and less costly treatment is required [4]. The quality of reclaimed water depends on several factors: Composition of the domestic water supply, presence of industrial waste, amount of infiltration into the sewage collection system, seasonal variations due to entry of storm water, use of water softeners, and wastewater treatment system characteristics. The impact of treatment system on water characteristics is discussed in Chapter 2 (Municipal Wastewater: Treatment and Reclaimed Water Characteristics) of this manual.

Water quality criteria for agricultural and landscape irrigation are well-established. These criteria can be used to evaluate both fresh water and reclaimed wastewater. Chapter 3 (Water Quality Criteria) and Chapter 7 (Water Management for Salinity and Sodicity Control) discuss this topic in depth.

Health and Environmental Aspects

The main goal of any wastewater treatment facility is to reduce health risks and prevent water pollution. When the wastewater effluent (reclaimed wastewater) from the facility is used for irrigation, consideration must also be given to potential hazards to farmers, farm workers, livestock, and consumers. Irrigation with reclaimed municipal wastewater has not resulted in any confirmed disease outbreaks in California, even though wastewater has been applied to land for many decades. Documented disease outbreaks in other parts of the world have always been associated with raw sewage or irrigation with undisinfected wastewater effluent. Because treatment cannot remove all pathogens, and because wastewater may contain other constituents of health concern, a conservative approach is promoted by public agencies involved in approval of land application of wastewater.

Health concerns are related to the degree of human contact, effluent quality, and the reliability of the treatment system. For example, regulations and criteria established by the California Department of Health Services recognize higher treatment requirements for irrigation of parks, playgrounds, and food crops, than for cemeteries, golf courses, and forage crops (see Chapter 10, Health and Regulatory Considerations).

Regarding movement of pathogens into groundwater following irrigation with reclaimed wastewater, there is general agreement that soil is an effective filter of pathogens, including viruses. Prudence is recommended in the handling of treated wastewater because bacteria, viruses, and helminth (worm) eggs may remain viable in soil for periods of several months or longer (see Chapter 14, Fate of Wastewater Constituents in Soil and Groundwater: Pathogens).

The concentration of trace elements in treated municipal wastewater is not high enough to result in short-term harmful effects, but metallic trace elements (for example, zinc, cadmium, nickel, lead, and copper) tend to accumulate in the soil. This subject is discussed in detail in Chapter 13 (Fate of Wastewater Constituents in Soil and Groundwater: Trace Elements) and Chapter 3 (Water Quality Criteria).

Recently, many potentially hazardous organic chemicals have been reported in wastewater, fresh water, and even in drinking water. However, they are usually at very low concentrations, and the environmental risks from trace organic substances associated with the use of reclaimed municipal wastewater should not be any greater than that associated with using other sources of water (see Chapter 15, Fate of Wastewater Constituents in Soil and Groundwater: Trace Organics).

Effects on Irrigation System Design and Farm Operation

Drastic changes in irrigation system design and operation as a result of using reclaimed municipal wastewater are not expected. Because of the need to control run-off and for other reasons, careful consideration must be given to site characteristics (see Chapter 4), design of the distribution system and storage facilities (see Chapter 8), and crop water requirements (see Chapter 5). Irrigation with reclaimed wastewater may require a change in crop or landscape species, modification in fertilizer application (to take into account nutrients in the reclaimed wastewater), modification of irrigation system design and management, and precautions taken to protect worker and consumer health.

Crop or landscape plant species selection may be affected by three factors: First, in California, the Wastewater Reclamation Criteria determine treatment requirements for irrigation of crop and landscape plants. For example, primary effluent may be used for fodder, fiber, and seed crops. Secondary or advanced treatment is required for food crops, landscaping, and pasture for milking animals. These criteria are discussed in Chapter 10 and are presented in their entirety in Appendix F of this manual. Second, plant species need to be selected that tolerate the levels of salt and other ions in the reclaimed wastewater. In most cases, this will not be an important selection criterion because reclaimed municipal wastewater is not much more saline than the original source water (see Chapters 2 and 3). Third, it may be desirable to select plant species that use a maximum amount of water and nitrogen. This would be the case where the amount of wastewater generated or the nitrogen contained in it exceeds the crop requirement. This would be reason to change from an annual row crop to a perennial grass forage species, for example. Fertilizer application can generally be reduced because of the nitrogen contained in reclaimed wastewater. Crop water use and nitrogen requirements are discussed in Chapters 5 (Crop Water Use) and 12 (Fate of Wastewater Constituents in Soil and Groundwater: Nitrogen and Phosphorus), respectively. A discussion of crop selection and forage management is presented in Chapter 6 (Crop Selection and Management).

Institutional and Legal Aspects

Governmental policy will influence the type of reuse planned. In 1977, the Office of Water Recycling was created within the California State Water Resources Control Board (SWRCB), with the goal of tripling wastewater reclamation and reuse [5]. The Federal Water Pollution Control Act Amendments of 1972 and the federal and state clean water grants programs have provided a financial incentive for wastewater reclamation and reuse. Other federal activities that encourage adoption of land application are U.S. Environmental Protection Agency (EPA) policy statements, regulations, and guidelines on federal cost-sharing, cost-effectiveness criteria, and public information and education programs. Key EPA policy statements indicate that the agency will press vigorously for publicly-owned treatment works to reclaim and recycle municipal effluents and sludges [6]. The 1976-77 drought in the western states provided another form of incentive for water conservation along with wastewater reclamation and reuse.

Currently in California, several agencies play an important role in encouraging and regulating wastewater reclamation and reuse. The Department of Health Services has established Wastewater Reclamation Criteria. The SWRCB administers federal and state clean water grant funds. The nine Regional Water Quality Control Boards prescribe and enforce waste discharge requirements, including the Wastewater Reclamation Criteria. Finally, local health agencies have independent authority and may choose to establish more stringent requirements than those set by the DOHS (see Chapter 10).

Legal concerns fall into two areas; both are discussed in Chapter 11 (Legal Aspects of Irrigation with Reclaimed Wastewater in

California). The first area is water rights, or put simply: Who owns the reclaimed water? A recent amendment to the California State Water Code states that it is the reclamation facility rather than the supplier of the water entering the plant which has the exclusive right to treated wastewater. But this amendment does not address the possible rights of downstream users. The author of Chapter 11 concludes that a wastewater treatment agency would be advised to obtain an appropriation permit from the SWRCB before diverting wastewater for reuse, especially if water that historically has been returned to a stream for reuse by others is to be diverted.

The second legal aspect of wastewater reclamation and reuse requiring attention is the contractual arrangement between the user(s) and the treatment agency. While no adverse impacts on health or crop marketability have been reported in California (Chapter 10), there is always the remote possibility that a third-party damage claim may be made. Even though hazards resulting from mismanagement, toxicities, or treatment failure are remote possibilities, they should be addressed in contracts for the sale of reclaimed wastewater. The author of Chapter 11 notes that the existing contracts in California "do not sufficiently clarify the mutual obligations of the parties". Several approaches to the assignment of liability are discussed in Chapter 11.

Economic Aspects

The economic value of reclaimed wastewater to the user (e.g., farmer or landscape manager) will depend upon (1) the availability and price of fresh water supplies and (2) the reclaimed wastewater supply characteristics. If fresh water is readily available at a low price, wastewater characteristics (for example, nutrient content) may still make the reclaimed wastewater attractive to a user.

Among many water supply characteristics, water quality ranks first in importance in irrigation with reclaimed municipal wastewater. Farmers in many parts of California enjoy some flexibility in choice of crop to be grown due to the moderate climate. Where poor water quality reduces that flexibility, the water is less valuable. A trade-off exists between the cost of treatment and the allowed uses. This limitation in the value of water is, however, typically not a problem in California: A 1977-78 Department of Health Services survey revealed that 72% of wastewater reclamation facilities (176 out of 243) provided a higher level of treatment than required by law for the existing uses of reclaimed wastewater [2].

Another important supply characteristic is the nutrient content, especially nitrogen. Nitrogen in reclaimed wastewater can substitute for fertilizer that would otherwise be purchased by the farmer. However, the amount of nitrogen applied in excess of crop needs has zero value and may have a negative value for crops such as citrus, sugarbeets, and cotton. They may have reduced yield or quality if nitrogen is applied in excess or at the wrong time. This problem can be resolved by blending with fresh water low in nitrogen.

The value of reclaimed wastewater also depends on how well the timing and quantity matches the demand for the water. If demand is low in the winter, the treatment agency may have to pay farmers to receive the water at that time. Off-season storage may be a better choice. Furthermore, the value of reclaimed wastewater may be less to a farmer if unreliability in its supply requires a back-up fresh water supply or if the possibility of excessive application requires investment in improved drainage and control of run-off (Chapter 9, On-Farm Economics of Reclaimed Wastewater Irrigation).

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CHAPTER 2

MUNICIPAL WASTEWATER: TREATMENT AND RECLAIMED WATER CHARACTERISTICS

Takashi Asano, Robert G. Smith, and George Tchobanoglous

INTRODUCTION

Although irrigation with wastewater is in itself an effective form of wastewater treatment (such as in slow-rate land treatment), some degree of treatment must be provided to untreated municipal wastewater before it can be used for agricultural or landscape irrigation. The degree of preapplication treatment is an important factor in the planning, design, and management of wastewater irrigation systems. The purpose of this chapter is to describe briefly (a) the principal processes used to achieve the various degrees of preapplication treatment and (b) the quality of the effluents produced. The information provided is intended primarily for those not familiar with municipal wastewater treatment or the characteristics of wastewater before and after treatment.

NEED FOR PREAPPLICATION TREATMENT

Preapplication treatment of wastewater is practiced for the following reasons:

1. Protect public health
2. Prevent nuisance conditions during storage
3. Prevent damage to crops and soils

In California, the State Department of Health Services (DOHS) establishes statewide wastewater reclamation criteria to ensure that the use of reclaimed water for the specific purposes does not pose undue risks to health [1]. The level of treatment required for agricultural and landscape irrigation uses depends on the soil characteristics, the crop irrigated, the type of distribution and application systems, and the degree of public exposure. These criteria are discussed in detail in Chapter 10 and are summarized in Table 10-3, p. 10-21. The level of treatment required for any type of wastewater reclamation and reuse or for discharge to receiving waters is specified in water reclamation or waste discharge permits issued by the California Regional Water Quality Control Boards. The criteria in Table 10-3 are incorporated into these permits as appropriate. The level of treatment required by regulatory agencies prior to irrigation of many crops is often not greater than, and is sometimes less than, the level of treatment required for discharge to receiving waters. Additional treatment to remove wastewater constituents that may be toxic or harmful to certain crops is technically possible but normally is not economically justified. To use waters containing such constituents, crops selected must be tolerant to wastewater constituents, and systems must be managed to mitigate harmful effects of constituents.

MUNICIPAL WASTEWATER CHARACTERISTICS

To discuss wastewater treatment processes and the characteristics of effluent produced by them, it is first necessary to describe the characteristics of untreated (raw) municipal wastewater.

Wastewater Sources

Wastewater is the general term applied to the liquid waste collected in sanitary sewers and treated in a municipal wastewater treatment plant (sewage treatment plant). Municipal wastewater is composed of domestic (sanitary) wastewater, industrial wastewater, and infiltration-inflow. Domestic wastewater is the spent water supply of the community after it has undergone a variety of uses in residences, commercial buildings, and institutions. Industrial wastewater is spent water from manufacturing or food-processing plants. Inflow is storm water that enters the sewer system through manhole and other openings, and infiltration is groundwater that seeps into the sewer through improperly sealed or broken joints or cracks in the pipe. The relative quantities of wastewater from each source vary widely among communities and depend on the number and type of commercial and industrial establishments as well as on the age and length of the sewer system.

In most communities, storm-water runoff is collected in a separate (storm) sewer system with no known domestic or industrial wastewater connections and is conveyed to the nearest watercourse for discharge without treatment. Several large cities in California have a combined sewer system in which both storm water and municipal wastewater are collected in the same sewer. During dry weather, flow in the combined sewers is intercepted and conveyed to the wastewater treatment plant for processing. During storms, flow in excess of the wastewater treatment plant capacity is either retained within the system and treated subsequently or is bypassed to the point of discharge.

Wastewater Flow Rates

The volume of wastewater generated in a community on a per capita basis varies from 50 to 150 gal/day (0.19 to 0.57 m^3/day) and includes domestic wastewater plus infiltration-inflow but excludes industrial wastewaters. The wide range of per-capita flows reflects differences in water consumption among communities and is largely a function of the price of water and reliability of the water supply. An average value of 100 gal/day (0.38 m^3/day) is often used for planning purposes in the absence of data specific to the community.

The short-term variations in wastewater flows observed at municipal wastewater treatment plants tend to follow a diurnal pattern. Flow is low during the early morning hours, when water consumption is lowest and when the base flow consists of infiltration-inflow and small quantities of sanitary wastewater. The first peak flow generally occurs in the late morning, when wastewater from the peak morning water use reaches the treatment plant. A second peak flow occurs in evening after the dinner hour. The relative magnitude of the peaks and the times at which they occur vary with the size of the community and the length of the sewers. Small communities with small sewer systems have a much higher ratio of peak flow to average flow than do large communities.

Although the magnitude of peaks is depressed as wastewater passes through a treatment plant, the daily variations in flow from a municipal treatment plant make it impractical, in most cases, to irrigate with effluent directly from the plant. Some form of flow-equalization or short-term storage of treated effluent is necessary to provide a relatively constant supply of reclaimed water for efficient irrigation. Additional benefits from storage are discussed later in the chapter.

Seasonal variations in wastewater flows are commonly observed at resort areas, in small communities with college campuses, and in communities that have seasonal commercial and industrial wastewater loads. An example is the substantially higher summer flows experienced by communities that receive industrial wastewater from seasonal food-processing industries.

Wastewater Constituents and Compositions

The physical properties and the chemical and biological constituents of wastewater are important parameters in the design and operation of collection, treatment, and disposal facilities and in the engineering management of environmental quality. The constituents of concern in wastewater treatment and wastewater irrigation are listed in Table 2-1. A complete evaluation and classification of water quality criteria for irrigation are presented in Chapter 3.

Composition refers to the actual amounts of physical, chemical, and biological constituents present in wastewater. The composition of untreated wastewater and the subsequently treated effluents depends upon the composition of the municipal water supply, the number and type of commerical and industrial establishments, and the nature of the residential community. Consequently, the composition of wastewater often varies widely among different communities. Typical data on the composition of untreated domestic wastewaters in the U.S. are presented in Table 2-2. Actual water-quality data for untreated wastewater entering selected plants in California are reported in Table 2-3. Wastewater-quality data routinely measured and reported are mostly in terms of gross pollutional parameters (e.g., biochemical oxygen demand, suspended solids, chemical oxygen demand) that are of interest in water pollution control (see Table 2-1). In contrast, the water characteristics of importance in agricultural or landscape irrigation are specific chemical elements and compounds that affect plant growth or soil permeability. These characteristics are not often measured or reported by wastewater-treatment agencies as part of their routine water-quality monitoring program. Consequently, when

Table 2-1. Constituents of concern in wastewater treatment and irrigation with reclaimed wastewater.

Constituent	Measured parameters	Reason for concern
Suspended solids	Suspended solids, including volatile and fixed solids	Suspended solids can lead to the development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the aquatic environment. Excessive amounts of suspended solids cause plugging in irrigation systems.
Biodegradable organics	Biochemical oxygen demand, Chemical oxygen demand	Composed principally of proteins, carbohydrates, and fats. If discharged to the environment, their biological decomposition can lead to the depletion of dissolved oxygen in receiving waters and to the development of septic conditions
Pathogens	Indicator organisms, total and fecal coliform bacteria	Communicable diseases can be transmitted by the pathogens in wastewater: bacteria, virus, parasites (See Chapter 10)
Nutrients	Nitrogen Phosphorus Potassium	Nitrogen, phosphorus, and potassium are essential nutrients for plant growth, and their presence normally enhances the value of the water for irrigation. When discharged to the aquatic environment, nitrogen and phosphorus can lead to the growth of undesirable aquatic life. When discharged in excessive amounts on land, nitrogen can also lead to the pollution of groundwater (See Chapter 12)
Stable (refractory) organics	Specific compounds (e.g., phenols, pesticides, chlorinated hydrocarbons)	These organics tend to resist conventional methods of wastewater treatment. Some organic compounds are toxic in the environment, and their presence may limit the suitability of the wastewater for irrigation (See Chapter 15)

Table 2-1 continued.

Constituent	Measured parameters	Reason for concern
Hydrogen ion activity	pH	The pH of wastewater affects metal solubility as well as alkalinity of soils. Normal range in municipal wastewater is pH = 6.5-8.5, but industrial waste can alter pH significantly
Heavy metals	Specific elements (e.g., Cd, Zn, Ni, Hg)	Some heavy metals accumulate in the environment and are toxic to plants and animals. Their presence may limit the suitability of the wastewater for irrigation (See Chapter 13)
Dissolved inorganics	Total dissolved solids, electrical conductivity, specific elements (e.g., Na, Ca, Mg, Cl, B)	Excessive salinity may damage some crops. Specific ions such as chloride, sodium, boron are toxic to some crops. Sodium may pose soil permeability problems (See Chapters 3 and 7)
Residual chlorine	Free and combined chlorine	Excessive amount of free available chlorine (>0.05 mg/L Cl_2) may cause leaf-tip burn and damage some sensitive crops. However, most chlorine in reclaimed wastewater is in a combined form, which does not cause crop damage. Some concerns are expressed as to the toxic effects of chlorinated organics in regard to groundwater contamination

Table 2-2. Typical composition of untreated municipal wastewater.[a]

Constituent	Concentration range[b] Strong	Medium	Weak	U.S. average[c]
Solids, total:	1,200	720	350	-
Dissolved, total[d]	850	500	250	-
Fixed	525	300	145	-
Volatile	325	200	105	-
Suspended	350	220	100	192
Fixed	75	55	20	-
Volatile	275	165	80	-
Settleable solids, mL/L	20	10	5	-
Biochemical oxygen demand, 5-day 20°C	400	220	110	181
Total organic carbon	290	160	80	102
Chemical oxygen demand	1,000	500	250	417
Nitrogen (total as N)	85	40	20	34
ORG-N	35	15	8	13
NH_3-N	50	25	12	20
NO_2-N	0	0	0	-
NO_3-N	0	0	0	0.6
Phosphorus (total as P)	15	8	4	9.4
Organic	5	3	1	2.6
Inorganic	10	5	3	6.8
Chlorides[d]	100	50	30	-
Alkalinity (as $CaCO_3$)[d]	200	100	50	211
Grease	150	100	50	-
Total coliform bacteria,[e] MPN/100 mL[f]	-	-	-	$22x10^6$
Fecal coliform bacteria,[e] MPN/100 mL	-	-	-	$8x10^6$
Viruses, PFU/100 mL[gh]	-	-	-	3.6

a. All values are expressed in mg/L, except as noted.
b. After Metcalf & Eddy, Inc., 1979 [2].
c. Culp et al., 1979 [3].
d. Values should be increased by amount in domestic water supply (see Table 2-4).
e. Geldreich, E. E., 1978 [4].
f. Most probable number/100 mL of water sample.
g. Berg and Metcalf, 1978 [5].
h. Plaque-forming units.

Table 2-3. Data on untreated municipal wastewater quality from selected treatment plants in California.[a]

Quality parameter	Plant location				
	Los Angeles County[b]				
	Joint Plant	Long Beach	Los Coyotes	Pomona	City of Davis[c]
Biochemical oxygen demand, 5-day	-	232	319	276	112
Total organic carbon	-	-	-	-	63.8
Suspended solids	-	284	331	325	185
Total nitrogen	-	41.6	43.1	34.6	43.4
NH_3-N	-	28.7	27.6	20.6	35.6
NO_3-N	-	-	-	-	0
Org-N	-	12.9	15.5	14.0	7.8
Total-P	-	34.6	35.9	28.3	-
Ortho-P	-	-	-	-	-
pH (unit)	-	-	-	-	7.7
Cations:					
Ca	78.8	66.0	74.4	63.6	-
Mg	25.6	21.2	19.3	14.4	-
Na	357	230	198	113	-
K	19	19	20	13	-
Anions:					
SO_4	270	257	175	111	-
Cl	397	186	205	123	-
Electrical conductivity, μmhos/cm	2,185	-	-	-	2,520
Total dissolved solids	1,404	1,125	930	573	-
Soluble sodium percentage, %	70.3	64.5	59.6	51.1	-
Sodium adsorption ratio	8.85	6.33	5.26	3.34	-
Boron (B)	1.68	0.76	0.95	0.59	-
Alkalinity ($CaCO_3$), total	322	374	320	268	-
Hardness ($CaCO_3$)	265	256	270	219	-

a. All values expressed in mg/L, except as noted.
b. County Sanitation District No. 2 of Los Angeles County, 1979 [6].
c. Smith and Schroeder, 1982 [7].

obtaining data to evaluate or plan a wastewater irrigation system, it is often necessary to sample and analyze the wastewater for those constituents that define the suitability of the water for agricultural or landscape irrigation.

The constituents that largely determine the suitability of a wastewater for agricultural or landscape irrigation are the dissolved inorganic solids or minerals (see Chapter 3). These constituents are not altered substantially in most wastewater-treatment processes; in some cases, they may increase as a result of evaporation in lagoons or storage reservoirs. Consequently, the composition of dissolved minerals in effluents used for irrigation can be expected to be similar to the composition in the untreated (raw) wastewater. The composition of dissolved minerals in untreated wastewater is determined by the composition of incoming domestic water supply plus mineral pickup resulting from domestic water use. Typical ranges of incremental mineral pickup that can be expected are reported in Table 2-4.

For purposes of planning, particularly in the absence of actual effluent data, the composition of dissolved minerals in treated effluents can be estimated from data on the water supply quality and from the values reported in Table 2-4. However, communities having large numbers of domestic and industrial water softeners can expect considerably more (5 to 10 times) sodium and chloride pickup than indicated in Table 2-4. An example of salt pickup from water softeners is provided in Chapter 3.

Municipal wastewater may contain pathogens of fecal origin including bacteria, viruses, protozoa, and parasitic worms. In areas where sanitary disposal of human feces is not practiced, diseases caused by these organisms, such as typhoid fever, bacillary dysentery, hepatitis, and poliomyelitis, are common. Because pathogens in water and wastewater are relatively few in number and difficult to isolate, the nonpathogenic coliform group of bacteria, which is more numerous and easily tested for, is used as an indicator of the presence of enteric pathogens in treated effluent and reclaimed water. Coliform bacteria are excreted in large numbers in the feces of humans and other warm-blooded animals, averaging about 50 million coliforms per

Table 2-4. Typical mineral pickup resulting from domestic water use.[a]

Constituent	Increment range[b] (mg/L)
Anions:	
Bicarbonate (HCO_3)	50 - 100
Carbonate (CO_3)	0 - 10
Chloride (Cl)	20 - 50[c]
Phosphate (PO_4)	5 - 15
Sulfate (SO_4)	15 - 30
Cations:	
Ammonium (NH_4)	15 - 40
Calcium (Ca) (as $CaCO_3$)	15 - 40
Magnesium (Mg) (as $CaCO_3$)	15 - 40
Potassium (K)	7 - 15
Sodium (Na)	40 - 70
Other constituents:	
Aluminum (Al)	0.1 - 0.2
Boron (B)	0.1 - 0.4
Iron (Fe)	0.2 - 0.4
Manganese (Mn)	0.2 - 0.4
Silica (SiO_2)	2 - 10
Total alkalinity (as $CaCO_3$)	100 - 150
Total dissolved solids	150 - 400

a. After Metcalf and Eddy, Inc., 1979 [2].

b. Reported national range of mineral pickup by domestic use. Does not include commercial and industrial additions.

c. Excluding the addition from home water softeners.

gram of feces. Untreated domestic wastewater contains millions of coliforms per 100 mL (see Table 2-2). Consequently, the presence of coliform bacteria is taken as an indication that pathogens may be present, and the absence of coliforms is taken as an indication that the water is free from pathogens.

MUNICIPAL WASTEWATER TREATMENT AND EFFLUENT CHARACTERISTICS

Municipal wastewater treatment consists of a combination of physical, chemical, and biological processes and operations to remove solids, organic matter, pathogens, and sometimes nutrients from wastewater. General terms used to describe different degrees of treatment, in order of increasing treatment level, are preliminary, primary, secondary, and advanced treatment. A disinfection step to remove pathogens usually follows the last treatment step.

The individual processes and operations commonly used in the various wastewater treatment steps are briefly described in this section. A generalized wastewater treatment flowsheet is shown in Figure 2-1. The quality of effluent produced by each treatment step is described using effluent-quality data from selected treatment plants in California. These data, particularly those for dissolved solids, are intended as examples only and should not be used as typical values for planning and design in lieu of specific data for the wastewater under consideration. As suggested previously, to assess the suitability of reclaimed wastewater for irrigation, the wastewater in question should be sampled and analyzed if complete water-quality data are not available.

Preliminary Treatment

Preliminary treatment operations include coarse screening and comminution of large objects and grit removal by sedimentation. In grit chambers, the velocity of the water through the chamber is maintained sufficiently high to prevent settling of most organic solids. In most small wastewater treatment plants, grit removal is not included as a preliminary treatment step.

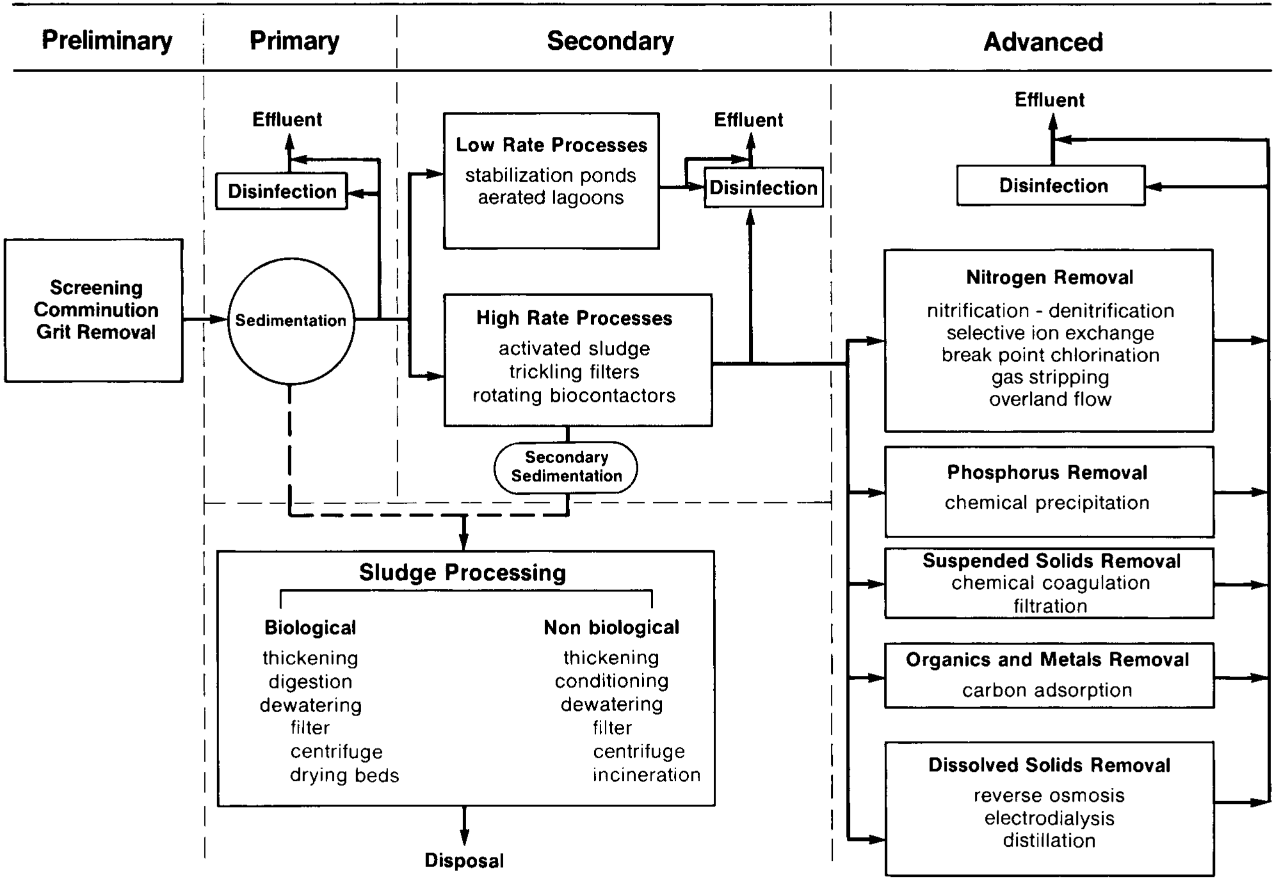

Figure 2-1. Generalized flow sheet for wastewater treatment.

Primary Treatment

The objective of primary treatment is the removal of settleable organic and inorganic solids by sedimentation, and the removal of materials that will float (scum) by skimming. Approximately 25% to 50% of the incoming biochemical oxygen demand (BOD), 35% to 50% of the chemical oxygen demand (COD), 50% to 70% of the total suspended solids (SS), and 65% of the oil and grease are removed during primary sedimentation. Some organic nitrogen, organic phosphorus, and heavy metals are also removed during primary sedimentation, but colloidal and dissolved constituents are not. The effluent from primary sedimentation facilities is referred to as primary effluent. Data on primary effluent quality from selected treatment plants in California are reported in Table 2-5.

In California, primary treatment is the minimum level of preapplication treatment required for wastewater irrigation. It is considered sufficient treatment if the wastewater is used to irrigate crops that are not consumed by humans (see Table 10-3, p. 10-21) and may be sufficient treatment for irrigation of orchards, vineyards, and some processed food crops. However, to prevent potential nuisance conditions in storage or equalizing reservoirs, some form of secondary treatment will normally be required by the California Regional Water Quality Control Boards, even in the case of non-food-crop irrigation. It may be possible to use at least a portion of primary effluent for irrigation if off-line storage is provided. The off-line storage concept is discussed in Chapter 8.

Primary sedimentation tanks or clarifiers may be round or rectangular basins, typically 10 to 15 ft (3.0 to 4.6 m) deep. Hydraulic detention times range between 2 and 3 hours. Settled solids (primary sludge) are removed from the bottom of tanks by sludge rakes that scrape the sludge into a hopper, from which it is pumped to sludge processing units. Scum is swept across the tank surface to a scum skimmer by water jets or mechanical means. Scum is also pumped to the sludge-processing units.

Primary sludge is most commonly processed biologically by anaerobic digestion. In the digestion process, bacteria metabolize the organic material in sludge, thereby reducing the volume requiring

Table 2-5. Data on quality of primary effluent from selected treatment plants in California.[a]

Quality parameter	Joint Plant[b]	Arroyo Grande[c]	Santa Barbara[c]	Ventura (Seaside)[c]	East Bay MUD (No.1)[c]	City of Davis[d]
	Plant location					
Biochemical oxygen demand	204	123	110	162	216	72.5
Total organic carbon	-	-	-	-	-	40.6
Suspended solids	219	-	-	-	102	71.6
Total nitrogen	-	51	21	35	41.7	34.7
NH_3-N	39.5	41	16	25	11.6	26.2
NO_3-N	-	0	0	0	1.4	0
Org-N	14.9	-	-	-	-	8.5
Total-P	11.2	12	14	10	7.5	-
pH (unit)	-	-	7.7	7.6	6.8	7.5
Cations:						
Ca	-	11.9	134	102	31	-
Mg	-	3.4	42	46	14	-
Na	359	330	460	320	209	-
K	19	13	24	18	33	-
Anions:						
SO_4	276	70	222	289	133	-
Cl	396	582	657	395	264	-
Electrical conductivity, μmhos/cm	-	2,300	2,850	-	-	2,340
Total dissolved solids	1,406	1,344	1,898	1,440	935	-
Sodium adsorption ratio	6.8	8.9	6.6	7.8	7.9	-
Boron (B)	1.5	0.60	0.95	1.0	-	-
Alkalinity ($CaCO_3$), total	332	1,040	735	-	131	-

a. All values expressed in mg/L, except as noted.
b. County Sanitation District No. 2 of Los Angeles County, 1979 [6].
c. Pound and Crites, 1973 [8].
d. Smith and Schroeder, 1982 [7].

ultimate disposal, rendering it stable (nonputrescible) and improving the dewatering characteristics of the sludge. Digestion is carried out in covered tanks (anaerobic digestors), typically 25 to 45 ft (7.6 to 14 m) deep. The residence time in a digestor may vary from a minimum of about 10 days for high-rate digestors (well mixed and heated) to 60 days or more in standard-rate digestors. Gas containing about 60% to 65% methane is produced during digestion and can be recovered as an energy source.

Secondary Treatment

Secondary treatment is the level of preapplication treatment required when the risk of public exposure to wastewater is moderate (see Table 10-5 in Chapter 10). In most cases, secondary treatment follows primary treatment and involves the removal of biodegradable dissolved and colloidal organic matter using aerobic biological treatment processes. Aerobic biological treatment is performed in the presence of oxygen by aerobic microorganisms (principally bacteria) that metabolize the organic matter in the wastewater, thereby producing more microorganisms and inorganic end-products (principally CO_2, NH_3, and H_2O). Several aerobic biological processes are used for secondary treatment. The processes differ primarily in the manner in which oxygen is supplied to the microorganisms and in the rate at which organisms metabolize the organic matter. For purpose of this discussion, biological wastewater treatment processes are grouped into high- and low-rate processes.

<u>High-Rate Biological Processes</u>

High-rate biological processes are characterized by relatively small basin volumes and high concentrations of microorganisms compared with the low-rate processes. Consequently, the growth rate of new organisms is much greater in high-rate systems because of a well-controlled environment. The microorganisms must be separated from the treated wastewater by sedimentation to produce the clarified secondary effluent. The sedimentation tanks used in secondary treatment, often referred to as secondary clarifiers, operate in the same basic manner as the primary clarifiers described previously. The biological solids removed during secondary sedimentation, called secondary or biological sludge, are normally combined with primary sludge for sludge processing.

Common high-rate processes include the activated sludge processes, trickling filters or biofilters, and rotating biological contactors (RBC). A combination of two of these processes in series (e.g., biofilter followed by activated sludge) is sometimes used to treat municipal wastewater containing a high concentration of organic material from industrial sources.

In the activated sludge process, the reactor is an aeration tank or basin containing a suspension of the wastewater and microorganisms. The contents of the aeration tank are mixed vigorously by aeration devices that also supply oxygen to the biological suspension. Aeration devices commonly used include submerged diffusers that release compressed air and mechanical surface aerators that introduce air by agitating the liquid surface. Hydraulic detention times in the aeration tanks range from 3 to 8 hours. Following the aeration step, the microorganisms are separated from the liquid by sedimentation. The clarified liquid is the secondary effluent. A portion of the biological sludge is recycled to the aeration basin. The remainder is removed from the process and sent to sludge processing to maintain a relatively constant concentration of microorganisms in the system. Several variations of the basic activated sludge process, such as extended aeration, are in common use, but the principles are similar.

A trickling filter or biofilter consists of a basin or tower filled with support media such as stones, plastic shapes, or wooden slats. Wastewater is applied intermittently, or sometimes continuously, over the media. Microorganisms become attached to the media and form a biological film layer. Organic matter in the wastewater diffuses into the film, where it is metabolized. Oxygen is normally supplied to the film by the natural flow of air either up or down through the media, depending on the relative temperatures of the wastewater and air. Forced air can also be supplied by blowers. The thickness of the biofilm increases as new organisms grow. Periodically, portions of the film slough off the media. The sloughed material is separated from the liquid in a secondary clarifier and discharged to sludge processing. Clarified liquid from the secondary clarifier is the secondary effluent. A portion of the effluent is normally recycled to the biofilter to improve hydraulic distribution of the wastewater over the filter.

Rotating biological contactors (RBCs) are similar to biofilters in that organisms are attached to support media. In the case of RBC, the support media are rotating discs that are partially submerged in flowing wastewater. Oxygen is supplied to the attached biofilm from the air when the film is out of the water. Some oxygen is also supplied to the wastewater by the agitation of the disc. Sloughed pieces of biofilm are removed in the same manner described for biofilters.

High-rate biological treatment processes, in combination with primary sedimentation, typically remove 85% to 95% of BOD and SS originally present in the wastewater and most of the heavy metals. Activated sludge generally produces an effluent of slightly higher quality, in terms of these constituents, than biofilters or RBCs. When coupled with a disinfection step, these processes provide substantial but not complete removal of bacteria and virus. These processes, however, remove very little phosphorus, nitrogen, nonbiodegradable organics, and dissolved minerals. Data on effluent quality from selected secondary treatment plants in California are presented in Table 2-6.

Low-Rate Biological Processes

Low-rate biological processes are characterized by microorganisms suspended in the wastewater in large basins that are typically earthen ponds or lagoons. The concentration of microorganisms in the basin and their growth rate are lower than in the high-rate biological systems, and the microorganisms are not usually separated from the liquid. In small treatment plants, primary sedimentation prior to low-rate processes is often omitted. Commonly used low-rate biological processes include aerated lagoons and stabilization ponds.

Aerated lagoons are characterized by hydraulic detention times of 7 to 20 days and water depths of 8 ft (2.4 m) or more in the basin. Oxygen is usually supplied to the basin by mechanical surface aerators

Table 2-6. Data on secondary effluent quality from selected treatment plants in California with high-rate biological processes.[a]

Quality parameter	Trickling filter: Chino Basin MWD (No.1)[b]	Activated sludge: Chino Basin MWD (No.2)[b]	Activated sludge: Santa Rosa Laguna[c]	Activated sludge: Montecito Sanitary District[d]
Biochemical oxygen demand	21	8	-	11
Chemical oxygen demand	-	-	27	-
Suspended solids	18	26	-	13
Total nitrogen	-	-	-	-
NH_3-N	25	11	10	1.4
NO_3-N	0.7	19	8	5
Org-N	-	-	1.7	-
Total-P	-	-	12.5	6
Ortho-P	-	-	3.4	-
pH (unit)	-	-	-	7.6
Cations:				
Ca	43	55	41	82
Mg	12	18	18	33
Na	83	102	94	-
K	17	20	11	-
Anions:				
HCO_3	293	192	165	-
SO_4	85	143	66	192
Cl	81	90	121	245
Electrical conductivity, μmhos/cm	-	-	-	1,390
Total dissolved solids	476	591	484	940
Sodium adsorption ratio	2.9	3.1	3.9	3.7
Boron (B)	0.7	0.6	0.6	0.7
Alkalinity ($CaCO_3$), total	-	-	-	226
Hardness ($CaCO_3$), total	156	200	175	365

a. Values expressed in mg/L, except as noted.
b. Metcalf & Eddy, 1981 [9].
c. Koretsky King et al., 1980 [10].
d. CH_2M-Hill, 1980 [11].

that agitate the water surface, although submerged air-diffusion devices have been used. Only the upper layer of the liquid in the basin is normally mixed, and an anaerobic zone develops near the bottom of the lagoon. Organic solids that settle to the bottom of the lagoon are decomposed by anaerobic bacteria.

Stabilization ponds (also called oxidation ponds) use algae to supply oxygen to the basin. The basin is mixed only by periodic wave action and thermal currents. Hydraulic detention times range from 20 to 30 days or more, and depths are typically 6 to 8 ft (1.8 to 2.4 m). Only the upper 3 to 4 ft (0.9 to 1.2 m) remain aerobic.

Low-rate biological processes are less costly and require less process control than high-rate processes; however, because solids are not separated from the liquid in most cases, the quality of the effluents from these processes is substantially lower than that from high-rate processes, particularly in terms of suspended solids due to algal growth. Consequently, the low-rate processes are seldom used for preapplication treatment when advanced treatment is required in combination with secondary treatment or when the highest level of disinfection is required in combination with secondary treatment. However, low-rate biological processes provide a sufficient degree of preapplication treatment for all other types of irrigation for which secondary treatment is required and also provide sufficient treatment to prevent nuisance conditions in storage reservoirs. Table 10-3 (p. 10-20) should be consulted for level of treatment required for particular irrigation uses in California. Stabilization ponds also provide considerable nitrogen removal, depending on the temperature and detention time involved. Effluent-quality data from selected low-rate biological treatment plants in California are given in Table 2-7.

Advanced Treatment

Advanced treatment is employed when specific wastewater constituents must be removed but cannot be removed by secondary treatment. As shown in Figure 2-1, individual treatment processes are necessary to remove nitrogen, phosphorus, additional suspended solids, refractory organics, heavy metals, and dissolved solids. Because

Table 2-7. Data on secondary effluent quality from selected treatment plants in California with low-rate biological processes (aerated lagoons and oxidation ponds).[a]

Quality parameter	Santa Rosa West College[b]	Napa Sanitation District[c]	American Canyon County Water District[c]	City of Davis[d]
	Plant location			
Biochemical oxygen demand	-	39	45	12.2
Chemical oxygen demand	74	-	-	-
Total organic carbon	-	-	-	19.8
Suspended solids	-	160	120	62[e]/121[f]
Total nitrogen	-	14.4	18.3	13
NH_3-N	11	1.5	6.1	8
NO_3-N	0.7	2.2	1.2	1.0
Org-N	2.8	10.7	11	5.0
Total-P	17	5.5	8.6	-
Ortho-P	4.3	-	-	-
pH (unit)	-	7.7	7.5	-
Oil and grease	-	9.0	7.0	-
Cations:				
Ca	49	37	32	-
Mg	16	46	37	-
Na	90	410	100	-
K	10	27	20	-
Anions:				
HCO_3	233	295	327	-
SO_4	54	66	33	-
Cl	100	526	80	-
Electrical conductivity, µmhos/cm	-	2,390	922	-
Total dissolved solids	467	1,295	510	-
Soluble sodium percentage, %	3.4	74	46	-
Sodium adsorption ratio	14	-	-	-
Boron (B)	0.5	1.2	1.3	-
Alkalinity ($CaCO_3$), total	-	242	268	-
Hardness ($CaCO_3$), total	184	281	232	-

a. Values expressed as mg/L, except as noted.
b. Koretsky King et al., 1980 [10].
c. Brown and Caldwell, 1979 [12].
d. Smith and Schroeder, 1982 [7].
e. Winter.
f. Summer.

advanced treatment usually follows high-rate secondary treatments, it is sometimes referred to as tertiary treatment. However, advanced treatments are sometimes combined with primary or secondary treatment (e.g., chemical addition to primary clarifiers or aeration basins to remove phosphorus) or used in place of secondary treatment (e.g., overland flow treatment of primary effluent).

In terms of preapplication treatment for irrigation, advanced treatment is required by DOHS [1] for spray irrigation of food crops and landscape irrigation in parks, school yards, and playgrounds (see Table 10-3). In these situations, where probability of public exposure to the reclaimed water or residual constituents is high, the intent of the treatment criteria is to minimize the probability of human exposure to enteric viruses. Effective disinfection of viruses is believed to be inhibited by suspended and colloidal solids in the water. Therefore, these solids must be removed by advanced treatment before the disinfection step. The sequence of treatment processes specified in the criteria are: secondary treatment followed by chemical coagulation, sedimentation, filtration, and disinfection to 2.2 MPN per 100 mL. This level of treatment is assumed to produce an effluence free from detectable virus. Effluent-quality data from selected advanced wastewater treatment plants in California are reported in Table 2-8.

Disinfection

The disinfection process normally involves the injection of a chlorine solution at the head end of a chlorine contact basin. The chlorine dosage depends upon the strength of the wastewater and other factors, but dosages of 5 to 10 mg/L are common. Ozone may also be used for disinfection, but it is not in common use in the United States. Chlorine contact basins are usually rectangular channels with baffles to prevent short-circuiting, but all are designed to provide a contact time of at least 15 minutes. However, along with the advanced waste-treatment requirements, sometimes a chlorine contact time of as long as 120 minutes is required in the case of specific irrigation uses of reclaimed wastewater [1]. The bactericidal effects of chlorine and other disinfectants are dependent upon pH, contact time, and water temperature.

Table 2-8. Effluent-quality data from selected advanced wastewater treatment plants in California.[a,b]

Quality parameter	Long Beach[c]	Los Coyotes[c]	Pomona[c]	Dublin San Ramon[d]	City of Livermore[c]	Simi Valley CSD[e]
	Plant location					
Biochemical oxygen demand	5	9	4	2	3	4
Suspended solids	-	5	-	1	-	-
Total nitrogen	-	-	-	-	-	19
NH_3-N	3.3	13.6	11.4	0.1	1.0	16.6
NO_3-N	15.4	1.1	3	19.0	21.3	0.4
Org-N	2.2	2.5	1.3	0.2	2.6	2.3
Total-P	-	-	-	-	-	-
Ortho-P	30.8	23.9	21.7	28.5	16.5	-
pH (unit)	-	-	-	6.8	7.1	-
Oil and grease	-	-	-	-	-	3.1
Total coliform bacteria, MPN/100 mL[f]	-	-	-	2	4	-
Cations:						
Ca	54	65	58	-	-	-
Mg	17	18	14	-	-	-
Na	186	177	109	168	178	-
K	16	18	12	-	-	-
Anions:						
SO_4	212	181	123	-	-	202
Cl	155	184	105	147	178	110
Electrical conductivity, μmhos/cm	1,352	1,438	1,018	1,270	1,250	-
Total dissolved solids	867	827	570	-	-	585
Soluble sodium, %	63.2	59.2	51.7	-	-	-
Sodium adsorption ratio	5.53	4.94	3.37	4.6	5.7	-
Boron (B)	0.95	0.95	0.66	-	1.33	0.6
Alkalinity ($CaCO_3$), total	-	256	197	150	-	-
Hardness ($CaCO_3$), total	212	242	206	254	184	-

a. Advanced wastewater treatment in these plants follows high-rate secondary treatment and includes addition of chemical coagulants (alum + polymer) as necessary followed by filtration through sand or activated carbon media.

b. Values expressed in mg/L, except as noted.

c. County Sanitation District No. 2 of Los Angeles County, 1979 [6].

d. CH_2M-Hill, 1981 [13].

e. Engineering-Science, 1980 [14].

f. Most probable number/100 mL of water sample.

As mentioned previously, the effectiveness of disinfection is measured in terms of the concentration of indicator organisms (total coliform or fecal coliform bacteria) remaining in the effluent at the end of the chlorine contact basin. The number of organisms remaining are expressed in terms of the most probable number of organisms per 100 mL of water sample (MPN/100 mL). The levels of disinfection required for preapplication treatment for the various types of irrigation are listed in Table 10-3, p. 10-20.

Effluent Storage

Although not considered a step in the treatment process, a storage facility is, in most cases, a critical link between the treatment plant and the irrigation system. The reasons storage is needed are as follows [15]:

1. To equalize daily variations in flow from the treatment plant and to store excess when average wastewater flow exceeds irrigation demands; includes winter storage.
2. To meet peak irrigation demands in excess of the average wastewater flow.
3. To minimize disruptions in the operations of the treatment plant and irrigation system. Storage is used to provide insurance against the possibility of unsuitable reclaimed wastewater entering the irrigation system and to provide additional time to resolve temporary water-quality problems.
4. To provide additional treatment. Oxygen demands, suspended solids, nitrogen, and microorganisms are reduced during storage.

RELIABILITY OF WASTEWATER TREATMENT

The *Wastewater Reclamation Criteria* [1] contain both design and operational requirements necessary to ensure treatment reliability. Reliability features such as alarm systems, standby power supplies, treatment process duplications, emergency storage or disposal of inadequately treated wastewater, monitoring devices, and automatic controllers are specified. From a public-health standpoint, provisions for adequate and reliable disinfection are the most essential features of the wastewater treatment process. Where disinfection is required, several reliability features must be incorporated into the system to ensure uninterrupted chlorine feed; these are cited in the *Wastewater Reclamation Criteria* [1]. Surveys have shown that good and consistent operation and maintenance of wastewater treatment facilities should be the highest priority in wastewater reclamation and reuse.

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CHAPTER 3

IRRIGATION WATER QUALITY CRITERIA

Dennis W. Westcot and Robert S. Ayers

INTRODUCTION

The quality of treated municipal wastewater depends to a great extent on the quality of the municipal water supply, nature of the wastes added during use, and the degree of treatment the wastewater has received. Generally, if the supply water used by the municipality is of acceptable quality for irrigation, the treated municipal wastewater will also be of acceptable quality, although somewhat degraded. There are few instances in California where treated municipal wastewater quality is so poor as to prevent its use for crop and landscape irrigation. The main exceptions would be in areas where salty groundwater seeps into wastewater collection systems or industrial wastes with an unacceptable contaminant are discharged into municipal wastewater collection systems. Because wastewaters contain impurities, careful consideration must be given to water quality in order to evaluate the possible long-term effects on soils and plants from salts, nutrients, and trace elements that occur naturally or are added during use or treatment. These effects are normally manageable if problems associated with these impurities are understood and allowances are made for them.

This chapter concentrates on how to evaluate the chemical quality of treated wastewater for use in irrigating plants. As such, it does not cover water quality evaluation from standpoints of health, groundwater, or environmental protection. Other chapters in this Guidance Manual cover how to manage these water quality related problems. Specific reference is made to Chapter 7, which covers management for salinity and sodicity control and to Chapter 13, which deals with trace elements. It is assumed throughout this chapter that the wastewater receives at least primary treatment and normally secondary biological treatment before reuse and that it has been disinfected by chlorination or similar treatment (see Chapter 2). Public health precautions and regulatory aspects are discussed in Chapters 10 and 14.

WASTEWATER SAMPLING

Laboratory results are only as reliable as the sample submitted for analysis. The sample should be representative of the conditions of irrigation use. There are no strict rules on sampling locations, timing, and handling, but a short discussion of sampling procedures may assist the user in obtaining a representative sample.

Sample Bottles

They should be clean. Before sample collection, rinse the bottle at least three times with the water to be sampled. For general chemical analysis, either glass or plastic bottles are usable, although plastic is preferred, as certain types of glass bottles yield boron to the sample. When sampling for trace elements, consult the laboratory for restrictions on the type of sampling container. In general, a plastic container is used for sampling trace elements, and after collection, 1 to 2 mL of concentrated nitric acid (HNO_3) is added to acidify the sample; this ensures that the trace elements remain in solution. Checking for nitrogen requires a second sample be taken without the addition of nitric acid.

Field Observation

Label all samples at the sampling point and cross reference in a field notebook. Make observations on sampling site condition including location, time, date, weather, water flow rate, water temperature, and other pertinent data. Before sampling, determine the analytical procedures to be used and the volume of sample needed, as certain analyses require special sample preparation or sample splitting. Some may require a large volume or special handling. For example, samples taken for trace elements, such as copper (Cu), that have acid added at the sampling point will need to have separate samples or split samples for bicarbonate, carbonate, nitrogen, and pH that do not have acid added.

Safety and Handling

Probably the greatest concern with treated wastewater sampling is disease transmission. Sampling and handling can be done safely if suitable precautions are taken. Use plastic gloves or other protection when sampling. More important, however, is preventive hygiene: avoid splashing the wastewater on hands, face, and body, and wash hands and face with soap after field sampling is completed. Tightly close all sample bottles, and clean the outside of the bottles. Label the sample and always mark WASTEWATER to alert the laboratory staff as to the source of sample.

Sample Location

The sample should represent, as closely as possible, the reclaimed water at the point of reuse; this is normally the discharge point. Make no attempt to sample for daily variations in quality or between different steps in the wastewater treatment plant. These water quality fluctuations are normally small by agricultural standards. Monthly or seasonal variation may be important in choosing a sampling location or sampling frequency. If polishing or holding ponds are used, take water samples as the wastewater leaves the ponds or, better yet, at the point of reuse, because important changes take place during storage and transport to the point of use.

Sampling Frequency

There are no specific requirements in California on the frequency of sampling reclaimed wastewater used for irrigation. For planning an irrigation scheme, take initial samples in spring, summer, fall, and winter. Later samplings are then timed to be representative of periods of (1) maximum salinity, (2) minimum salinity, (3) maximum nitrogen, and (4) minimum nitrogen. After the initial sampling, the regulatory agencies like to have quarterly samples taken for all major cations and anions, and a minimum of one sample per year for the trace elements. If only one annual sample is to be relied upon for management decisions, sample water from either the preplant irrigation or initial irrigation for germination or early growth period. Plants are most sensitive or responsive during germination and early growth.

WATER ANALYSIS

Irrigation water quality appraisal does not require the degree of accuracy in analysis that is common to a research study. The main objective of water analysis for agricultural use is to obtain an indication of potential problems from which management decisions can be made. Use the most appropriate method for the available equipment, budget, and number of samples, provided the results are consistent and reproducible within ±10%.

There are several recognized procedures for laboratory analysis of water including the following: *U.S. Salinity Laboratory Memo Report* [1], *USDA Agricultural Handbook 60* [2], *Standard Methods for the Examination of Water and Wastewater* [3], *California Soil Testing Procedures* [4], and *Methods of Analysis of Soil, Plants and Waters* [5]. Many commercial laboratories routinely measure the needed irrigation water quality parameters.

A list of laboratory determinations needed to evaluate water quality for irrigation is given in Table 3-1 along with the symbols and units used and the usual range of concentrations found in irrigation waters. These data are adequate to evaluate the suitability as an irrigation water and to assess the water's potential to cause common soil and plant problems.

Salinity in Table 3-1 refers to the quantity and type of salts dissolved in the irrigation water. It is usually determined by measuring the electrical conductivity of the water (EC_w); the saltier the water, the greater its conductivity. Easily used field and laboratory instruments are available, which make this one of the more commonly measured parameters.

The SAR (sodium adsorption ratio) is a calculated value and an indicator of the probable influence the sodium ion has on soil properties. The calculation procedure is shown in Table 3-1. Table 3-2 gives a procedure for adjusting the SAR value to include a more correct estimate of calcium in the soil water following an irrigation. It is important to calculate the SAR or the adjusted value for reclaimed wastewaters, as they tend to have an appreciably higher SAR than a non-wastewater irrigation supply.

Table 3-3 lists additional determinations that are frequently needed when using reclaimed municipal wastewater for irrigation. It is recommended that nutrient levels be determined annually on all wastewaters. Of the nutrients listed in Table 3-3, nitrogen is the

Table 3-1. Laboratory determinations needed to evaluate common irrigation water quality problems.

Water parameter	Symbol	Unit	Usual range in irrigation water
<u>Salinity</u>			
Salt content			
Electrical conductivity	EC_w	mmho/cm or dS/m	0 - 3
Total dissolved solids	TDS	mg/L	0 - 2000
Cations and anions			
Calcium	Ca^{++}	mg/L	0 - 400
Magnesium	Mg^{++}	mg/L	0 - 60
Sodium	Na^{+}	mg/L	0 - 900
Carbonate	CO_3^{--}	mg/L	0 - 3
Bicarbonate	HCO_3^{-}	mg/L	0 - 600
Chloride	Cl^{-}	mg/L	0 - 1100
Sulfate	SO_4^{--}	mg/L	0 - 1000
<u>Miscellaneous</u>			
Boron	B	mg/L	0 - 2
pH (hydrogen ion activity)	pH		6.5- 8.5
Sodium adsorption ratio	SAR[a,b] or R_{Na}		0 - 15

a. SAR is calculated from the following equation:

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}}$$

Where Na, Ca and Mg are in meq/L.

$$Na \text{ (in meq/L)} = \frac{Na \text{ in mg/L}}{23}$$

$$Ca \text{ (in meq/L)} = \frac{Ca \text{ in mg/L}}{20}$$

$$Mg \text{ (in meq/L)} = \frac{Mg \text{ in mg/L}}{12.2}$$

$$HCO_3 \text{ (in meq/L)} = \frac{HCO_3 \text{ in mg/L}}{61}$$

b. For wastewaters, the SAR may need to be adjusted to include a more correct estimate of the calcium that can be expected to remain in the soil water after an irrigation. This adjusted sodium adsorption ratio (adj R_{Na}) is calculated using the adjustment procedure of Table 3-2.

Table 3-2. Calculation of adjusted R_{Na} [a,b,c]

The adjusted sodium adsorption ratio (adj R_{Na}) for the soil surface is calculated from the following equation:

$$\text{adj } R_{Na} = \frac{Na}{\sqrt{\dfrac{Ca_x + Mg}{2}}}$$

where Na and Mg in milliequivalents per liter (meq/L) are taken from the water analysis and Ca_x is obtained from the table below. To use the table, the applied water salinity (EC_w) in mmho/cm or in dS/m and the bicarbonate to calcium ratio (HCO_3/Ca) using milliequivalents per liter must be known from the water analysis.

Ca_x values for near surface soil-water at various applied water salinities and HCO_3/Ca ratios assuming equilibrium conditions for soil-water, no precipitation of magnesium and a partial pressure of CO_2 (P_{CO_2}) of 0.0007 atmospheres.

Ratio of HCO_3/Ca	Salinity of applied water (EC_w) (mmho/cm or dS/m)											
	0.1	0.2	0.3	0.5	0.7	1.0	1.5	2.0	3.0	4.0	6.0	8.0
.05	13.20	13.61	13.92	14.40	14.79	15.26	15.91	16.43	17.28	17.97	19.07	19.94
.10	8.31	8.57	8.77	9.07	9.31	9.62	10.02	10.35	10.89	11.32	12.01	12.56
.15	6.34	6.54	6.69	6.92	7.11	7.34	7.65	7.90	8.31	8.64	9.17	9.58
.20	5.24	5.40	5.52	5.71	5.87	6.06	6.31	6.52	6.86	7.13	7.57	7.91
.25	4.51	4.65	4.76	4.92	5.06	5.22	5.44	5.62	5.91	6.15	6.52	6.82
.30	4.00	4.12	4.21	4.36	4.48	4.62	4.82	4.98	5.24	5.44	5.77	6.04
.35	3.61	3.72	3.80	3.94	4.04	4.17	4.35	4.49	4.72	4.91	5.21	5.45
.40	3.30	3.40	3.48	3.60	3.70	3.82	3.98	4.11	4.32	4.49	4.77	4.98
.45	3.05	3.14	3.22	3.33	3.42	3.53	3.68	3.80	4.00	4.15	4.41	4.61
.50	2.84	2.93	3.00	3.10	3.19	3.29	3.43	3.54	3.72	3.87	4.11	4.30
.75	2.17	2.24	2.29	2.37	2.43	2.51	2.62	2.70	2.84	2.95	3.14	3.28
1.0	1.79	1.85	1.89	1.96	2.01	2.09	2.16	2.23	2.35	2.44	2.59	2.71
1.25	1.54	1.59	1.63	1.68	1.73	1.78	1.86	1.92	2.02	2.10	2.23	2.33
1.50	1.37	1.41	1.44	1.49	1.53	1.58	1.65	1.70	1.79	1.86	1.97	2.07
1.75	1.23	1.27	1.30	1.35	1.38	1.43	1.49	1.54	1.62	1.68	1.78	1.86
2.00	1.13	1.16	1.19	1.23	1.26	1.31	1.36	1.40	1.48	1.54	1.63	1.70
2.25	1.04	1.08	1.10	1.14	1.17	1.21	1.26	1.30	1.37	1.42	1.51	1.58
2.50	0.97	1.00	1.02	1.06	1.09	1.12	1.17	1.21	1.27	1.32	1.40	1.47
3.00	0.85	0.89	0.91	0.94	0.96	1.00	1.04	1.07	1.13	1.17	1.24	1.30
3.50	0.78	0.80	0.82	0.85	0.87	0.90	0.94	0.97	1.02	1.06	1.12	1.17
4.00	0.71	0.73	0.75	0.78	0.80	0.82	0.86	0.88	0.93	0.97	1.03	1.07
4.50	0.66	0.68	0.69	0.72	0.74	0.76	0.79	0.82	0.86	0.90	0.95	0.99
5.00	0.61	0.63	0.65	0.67	0.69	0.71	0.74	0.76	0.80	0.83	0.88	0.93
7.00	0.49	0.50	0.52	0.53	0.55	0.57	0.59	0.61	0.64	0.67	0.71	0.74
10.00	0.39	0.40	0.41	0.42	0.43	0.45	0.47	0.48	0.51	0.53	0.56	0.58
20.00	0.24	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.32	0.33	0.35	0.37

[a] Adapted from Suarez [6].

[b] The adjusted sodium adsorption ratio (adj R_{Na}) is a modification of the SAR procedure. It has long been recognized that calcium in the soil-water is not constant. The calcium concentration at equilibrium depends on both the concentration in the applied water and also the dissolution from soil-calcium or precipitation from soil-water. The effect is to raise or lower the relative sodium content in the soil-water. The calcium in solution at equilibrium is influenced by soil-water salinity and the concentration of calcium, bicarbonate, and dissolved carbon dioxide. The effects are reflected in the Ca_x value.

[c] The adjusted sodium adsorption ratio includes the effects of the factors noted in the above footnote and more correctly predicts the sodium hazard and potential infiltration problem caused by water quality. The adjusted sodium adsorption ratio (adj R_{Na}) may be substituted for the SAR value when evaluating the potential infiltration problem.

Table 3-3. Additional laboratory determinations needed to evaluate the suitability of reclaimed municipal wastewater for irrigation.

Nutrients[a] (in mg/L)

Nitrate-nitrogen (NO_3-N)	Total nitrogen (Total-N)
Ammonia-nitrogen (NH_3-N)	Ortho-phosphate-phosphorus (PO_4-P)
Organic-nitrogen (Org-N)	Total phosphorus (TP)
Potassium (K)	

Residual chlorine (Cl_2 in mg/L)

Trace elements[c]

	Typical detection limits (mg/L)[d]	
	AA spectrophotometer	ICAP spectrophotometer
Group I		
Aluminum (Al)	0.03	0.02
Arsenic (As)	0.14	0.05
Barium (Ba)	0.008	0.0005
Cadmium (Cd)	0.0005	0.004
Chromium (Cr)	0.002	0.005
Copper (Cu)	0.001	0.003
Fluoride (F)	-	-
Iron (Fe)	0.003	0.003
Lead (Pb)	0.01	-
Lithium (Li)	0.0005	-
Manganese (Mn)	0.001	0.001
Mercury (Hg)	0.17	-
Nickel (Ni)	0.004	0.01
Selenium (Se)	0.07	0.05
Silver (Ag)	0.0009	-

Table 3-3 continued.

Vanadium (V)	0.04	0.005
Zinc (Zn)	0.0008	0.002
<u>Group II</u>		
Antimony (Sb)	0.03	-
Beryllium (Be)	-	-
Cobalt (Co)	0.006	0.006
Molybdenum (Mo)	0.03	0.008
Thallium (Tl)	0.009	-
Tin (Sn)	0.11	0.03
Titanium (Ti)	0.05	0.002
Tungsten (W)	1.2	0.04

a. For all nutrient analyses, the laboratory should report in terms of the chemically equivalent elemental nitrogen, phosphorus and potassium. This allows the user to compare between analyses. All concentrations of N, P and K should be reported in mg/L to a precision of ± 0.5 mg/L.

The following conversion factors may be helpful:

lb of N per acre-ft of water = mg/L of N in the water x 2.715
lb of P per acre-ft of water = mg/L of P in the water x 2.715
lb of K per acre-ft of water = mg/L of K in the water x 2.715
lb of P_2O_5 per acre-ft of water = mg/L of P in the water x 6.24
lb of K_2O per acre-ft of water = mg/L of K in the water x 3.25

b. Total nitrogen is calculated based on (NO_3-N) + (NH_3-N) + (Org-N). The KN (Kjeldahl Nitrogen) procedure is used to determine the organic nitrogen in the sample.

c. Routine checks for trace elements would not include Group II trace elements unless they were suspected of being present.

d. Most laboratories use both the Atomic Absorption Spectrophotometer (AA) or the Inductively Coupled Argon Plasma Emission Spectrophotometer (ICAP). Where more accurate analysis of arsenic (As), lead (Pb), mercury (Hg), molybdenum (Mo), and tin (Sn) is desired, either the HGA Graphite Furnace Method or the Hydride Systems Method should be used. Consult the laboratory for cost and availability.

most variable. There is no hard-and-fast rule for the form that nitrogen takes, therefore, include each of the forms of nitrogen and calculate a total nitrogen during initial analyses. Later analyses may be modified to monitor only the more important nitrogen forms or total nitrogen.

Until recently, the difficulty and expense of laboratory analyses prevented routine trace element analysis. Improved detection methods and lower costs now make trace element analysis routine in most laboratories. It is recommended that all trace elements listed in Group I in Table 3-3 be determined on a composite sample at least once before initial irrigation use, followed by periodic checks made for those elements found in significant and important quantities.

With the laboratory data from Tables 3-1 and 3-3, an appraisal of potential water quality related problems can be made. The laboratory data help the trained fieldman, agronomist, soil scientist, or engineer better understand, interpret, and (it is hoped) improve crop yields. The reclaimed wastewater user, however, must constantly guard against drawing unwarranted conclusions based strictly on laboratory results alone.

WATER QUALITY EVALUATION

All waters contain measurable quantities of dissolved salts. In California, surface water supplies generally have lower levels of salt than groundwaters. The majority of cities, however, take their water supplies from groundwater, which varies greatly in quality from one city well to another; therefore, the wastewater quality is also highly variable. As discussed in the previous section, the primary factor in evaluating water quality for irrigation is the quantity and kind of salt present in these water supplies.

As salinity increases in the reclaimed wastewater used for irrigation, the probability for certain soil, water, and cropping problems increases. These problems are related to the total salt content, to one or more types of salt, or to excessive concentrations of one or more trace elements. The problems, however, are no different from those caused by salinity or trace elements in freshwater supplies and are of concern only if they restrict the use of the water or require special management to maintain acceptable yields. For irrigation with reclaimed wastewater, therefore, the suitability of a water is judged against the level of management needed to cope successfully with the water related problems that are expected to develop during use.

It is not possible to cover all local situations when preparing water quality guidelines. The approach used here is to present guidelines that stress the management needed to successfully use water of a certain quality. Obviously, as the quality of water becomes poorer, the options become fewer and management becomes more critical. Of course, the exact choice of practices must be made at the farm or user level. Guidelines for evaluating irrigation water quality are given in Table 3-4.

The "Potential Restrictions in Use" shown in Table 3-4 are divided into three categories related to the management skill needed. The divisions are somewhat arbitrary, since changes occur gradually and there is no clear-cut breaking point. Changes of 10% to 20% above or below the guideline values may have little significance if considered in the proper perspective with other factors affecting yields. Many field studies, research trials, and observations have led to these guideline values, but the management skill of the water user may alter these values considerably. The values shown are applicable under the general field conditions prevailing in California's irrigated regions if no special management practices are adopted.

Full production capability of all crops is assumed when the guidelines indicate no restrictions on use. On the other hand, if water is used which equals or exceeds the values shown for "Severe" restrictions, the water user is likely to experience soil and cropping problems or reduced yields as a result of using this poor quality water. Severe restrictions mean special management practices are needed to allow successful production with water of the quality indicated. If quality values are between these two extremes, there are gradually increasing restrictions on crop selection and fewer management alternatives as the water quality deteriorates.

Table 3-4. Guidelines for interpretation of water quality for irrigation.[a]

Potential irrigation problem	Units	Degree of restriction on use: None	Slight to moderate	Severe
Salinity (affects crop water availability)				
EC_w[b]	dS/m or mmho/cm	<0.7	0.7 - 3.0	>3.0
TDS	mg/L	<450	450 - 2000	>2000
Permeability (affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)[c,d]				
SAR = 0 - 3		and EC_w = >0.7	0.7 - 0.2	<0.2
= 3 - 6		= >1.2	1.2 - 0.3	<0.3
= 6 - 12		= >1.9	1.9 - 0.5	<0.5
= 12 - 20		= >2.9	2.9 - 1.3	<1.3
= 20 - 40		= >5.0	5.0 - 2.9	<2.9
Specific ion toxicity (affects sensitive crops)				
Sodium (Na)[e,f]				
surface irrigation	SAR	<3	3 - 9	>9
sprinkler irrigation	mg/L	<70	>70	
Chloride (Cl)[e,f]				
surface irrigation	mg/L	<140	140 - 350	>350
sprinkler irrigation	mg/L	<100	>100	
Boron (B)	mg/L	<0.7	0.7 - 3.0	>3.0
Trace elements (see Table 3-5)				
Miscellaneous effects (affects susceptible crops)				
Nitrogen (Total-N)[g]	mg/L	<5	5 - 30	>30
Bicarbonate (HCO_3) (overhead sprinkling only)	mg/L	<90	90 - 500	>500
pH		Normal range 6.5 - 8.4		
Residual chlorine (overhead sprinkling only)	mg/L	<1.0	1.0 - 5.0	>5.0

a. Adapted from University of California Committee of Consultants [7] and Ayers and Westcot [8]. The basic assumptions of the guidelines are discussed on the second page of this table.

b. EC_w means electrical conductivity of the irrigation water, reported in mmho/cm or dS/m. TDS means total dissolved solids, reported in mg/L.

c. SAR means sodium adsorption ratio. SAR is sometimes reported as R_{Na}. See Table 3-1 for the SAR calculation procedures. At a given SAR, infiltration rate increases as salinity (EC_w) increases. Evaluate the potential permeability problem by SAR and EC_w in combination. Adapted from Rhoades [9] and Oster and Schroer [10] (see Figure 7-5).

d. For wastewaters, it is recommended that the SAR be adjusted to include a more correct estimate of calcium in the soil water following an irrigation. A procedure is given in Table 3-2. The adjusted sodium adsorption ratio (adj R_{Na}) calculated by this procedure is to be substituted for the SAR value.

e. Most tree crops and woody ornamentals are sensitive to sodium and chloride; use the values shown. Most annual crops are not sensitive; use the salinity tolerance tables (Tables 3-6 and 3-7). See Table 3-9 for chloride tolerances of specific fruit crops.

f. With overhead sprinkler irrigation and low humidity (<30%), sodium or chloride greater than 70 or 100 mg/L, respectively, have resulted in excessive leaf absorption and crop damage to sensitive crops (see Table 3-10).

g. Total nitrogen should include nitrate-nitrogen, ammonia-nitrogen, and organic-nitrogen. Although forms of nitrogen in wastewater vary, the plant responds to the total nitrogen.

Table 3-4 continued.

Assumptions in the Guidelines

The water quality guidelines in Table 3-4 are intended to cover the wide range of conditions encountered in California's irrigated agriculture. Several basic assumptions have been used to define the range of usability for these guidelines. If the water is used under greatly different conditions, the guidelines may need to be adjusted (See Chapter 7).

Wide deviations from the assumptions might result in wrong judgments on the usability of a particular water supply, especially if it is a borderline case. Where sufficient experience, field trials, research, or observations are available, the guidelines may be modified to more closely fit local conditions.

The basic assumptions in the guidelines are given below.

Yield Potential. Full production capability of all crops, without the use of special practices, is assumed when the guidelines indicate no restrictions on use. A "restriction on use" indicates that there may be a limitation such as choice of crop or the need for special management in order to maintain full production capability, but a "restriction on use" does not indicate that the water is unsuitable for use.

Site Conditions. Soil texture ranges from sandy-loam to clay with good internal drainage. Rainfall is low and does not play a significant role in meeting crop water demand or leaching. In the Sierra and extreme North Coast areas of California where precipitation is high for part or all of the year, the guideline restrictions are too severe. Drainage is assumed to be good, with no uncontrolled shallow water table present.

Methods and Timing of Irrigations. Normal surface and sprinkler irrigation methods are used. Water is applied infrequently as needed, and the crop utilizes a considerable portion of the available stored soil water (50% or more) before the next irrigation. At least 15% of the applied water percolates below the root zone (leaching fraction [LF] > 15%). The guidelines are too restrictive for specialized irrigation methods, such as drip irrigation, which result in near daily or frequent irrigations. The guidelines are not applicable for subsurface irrigation.

Water Uptake by Crops. Different crops have different water uptake patterns, but all take water from wherever it is most readily available within the root zone. Each irrigation leaches the upper root zone and maintains it at a relatively low salinity. Salinity increases with depth and is greatest in the lower part of the root zone. The average salinity of the soil solution is about three times that of the applied water.

Salts leached from the upper root zone accumulate to some extent in the lower part but eventually are moved below the root zone by sufficient leaching. The crop responds to average salinity of the root zone. The higher salinity in the lower root zone becomes less important if adequate moisture is maintained in the upper, "more active" part of the root zone.

The reporting units in Table 3-4 are given in the previous section on monitoring and laboratory evaluation. In some cases, these units are different from those used in sanitary engineering terminology. Certain assumptions are also made about how the water is used, but in general these assumptions reflect common practices of irrigation, including those used on municipal wastewater reclamation and reuse projects. The assumptions are given on the second page of Table 3-4; should conditions differ greatly, further references should be consulted.

In addition to the effects of total salinity on plant growth and soils, individual ions may cause growth reductions. Ions of both major and trace elements occur in irrigation water. Trace elements are those that normally occur in waters or soil solutions in concentrations less than a few mg/L with usual concentrations less than 100 µg/L. Some may be essential for plant growth at very low concentrations but quickly become toxic as the concentration increases. Others are nonessential [11].

The suggested maximum trace element concentrations for irrigation waters are shown in Table 3-5. Note, however, that the toxicities caused by these trace elements are not related to specific farm management practices. In most cases, these elements accumulate in plants and soils, and the concern is for their long-term buildup in the soil, which could result in human and animal health hazards or cause phytotoxicity in plants. This accumulation takes place regardless of the management used. The values given in Table 3-5 reflect those that would normally not adversely affect plants or soils if the irrigation water is used continuously at that site [11, 12].

The guidelines in Tables 3-4 and 3-5 are practical and usable for landscape irrigation and for irrigated agriculture in California. They are based on keeping the long-term soil and cropping situation economical: short-term gains from disposal of extra quantities of treated wastewater should not be at the expense of causing deterioration of soil and water resources.

In the following sections, further explanations of how the most common water quality problems develop may help in understanding the application of the guidelines given in Tables 3-4 and 3-5 and how

Table 3-5. Recommended maximum concentrations of trace elements in irrigation waters.[a]

Element	Recommended maximum concentration[b] (mg/L)	Remarks
Al (aluminum)	5.0	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH >5.5 will precipitate the ion and eliminate any toxicity.
As (arsenic)	0.10	Toxicity to plants varies widely, ranging from 12 mg/L for Sudan grass to less than 0.05 mg/L for rice.
Be (beryllium)	0.10	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans.
Cd (cadmium)	0.01	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L in nutrient solutions. Conservative limits recommended because of its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Co (cobalt)	0.05	Toxic to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Cr (chromium)	0.1	Not generally recognized as an essential growth element. Conservative limits recommended because of lack of knowledge on toxicity to plants.
Cu (copper)	0.2	Toxic to a number of plants at 0.1 to 1.0 mg/L in nutrient solutions.
F (fluoride)	1.0	Inactivated by neutral and alkaline soils.
Fe (iron)	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of reduced availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment, and buildings.
Li (lithium)	2.5	Tolerated by most crops up to 5 mg/L; mobile in soil. Toxic to citrus at low levels (>0.075 mg/L). Acts similar to boron.

Table 3-5 continued.

Element	Recommended maximum concentration[b] (mg/L)	Remarks
Mn (manganese)	0.2	Toxic to a number of crops at a few tenths mg to a few mg/L, but usually only in acid soils.
Mo (molybdenum)	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high levels of available molybdenum.
Ni (nickel)	0.2	Toxic to a number of plants at 0.5 to 1.0 mg/L; reduced toxicity at neutral or alkaline pH.
Pb (lead)	5.0	Can inhibit plant cell growth at very high concentrations.
Se (selenium)	0.02	Toxic to plants at concentrations as low as 0.025 mg/L and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. An essential element for animals but in very low concentrations.
Sn (tin)	---	Effectively excluded by plants; specific tolerance unknown.
Ti (titanium)	---	(See remark for tin.)
W (tungsten)	---	(See remark for tin.)
V (vanadium)	0.1	Toxic to many plants at relatively low concentrations.
Zn (zinc)	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH >6.0 and in fine textured or organic soils.

a. Adapted from Water Quality Criteria [11] and Pratt [12].

b. The maximum concentration is based on a water application rate that is consistent with good agricultural practices (4 acre-ft/acre·year). If the water application rate exceeds this, the maximum concentration should be adjusted downward accordingly. No adjustment should be made for application rates of less than 4 acre-ft per year per acre. The values given are for waters used on a continuous basis at one site for the irrigation supply water.

these guidelines can be applied to evaluate the suitability of a given wastewater for use on crops or landscapes.

Salinity

Salinity, measured by electrical conductivity, is the single most important parameter in determining the suitability of a water for irrigation. It relates directly to possible problems caused by the total salt load in the water. Plant damage from both salinity and specific ions is usually tied closely to an increase in salinity.

Salt is continually added to the soil with the irrigation water, and a problem occurs if the added salts accumulate to a concentration that is harmful to the crop or landscape. The rate of accumulation depends upon the quantity of salt applied in the irrigation water (salts in) and the rate at which salt is removed by leaching (salts out). Over an extended period, salts out must equal salts in. Fortunately, most salts are soluble and easily transported by the water added to soil. Applying more irrigation water than can be used by the crop assures that salt removal takes place (leaching). Establishing a net downward flux of water and salt through the root zone is the only practical way to manage a salinity problem. Under such conditions, good drainage is essential in order to allow a continuous movement of water and salt below the root zone.

In Table 3-4, it is assumed that under normal irrigation, a certain fraction of the applied water moves below the root zone to remove salts. This is called the leaching fraction. In Table 3-4, an average leaching fraction of 0.15 is assumed. Under this condition, no salinity problem is expected for waters having an EC_w <0.7 mmho/cm, (<0.7 dS/m) and no special management practices are required. But waters in the 0.7 to 3.0 mmho/cm (dS/m) range (slight to moderate salinity) may require special practices if full production is to be achieved. The need for these special practices increases as salinity increases. Waters with EC_w >3.0 mmho/cm (dS/m) require very intensive and careful management to control salinity including such drastic steps as changing to a more salt tolerant crop or greatly increasing the leaching fraction (see Chapter 7). Salt sensitive crops would show drastic yield reductions at EC_w >3.0 mmho/cm (dS/m) even under the best management. Table 3-6 gives recent data on the relative tolerance of many agricultural crops to salinity [13]. Although this list is only a relative ranking, it provides a good comparison of the performance of one crop relative to others. The tolerance ratings used in Table 3-6 are depicted in Figure 3-1. A similar tolerance rating is given in Table 3-7 for landscape plants. This landscape rating, however, is not based on economic yield: it is based on plant damage which may detract from the plant's desirability as landscape material. Reference [13] should be consulted for more exact tolerance ratings.

The above discussion assumes that salinity is controlled by leaching and that subsurface drainage is adequate. In areas without adequate drainage, shallow water tables can occur and become an additional major source of salts (water table within 3 to 6 ft of the land surface). Long-term use of reclaimed wastewater for irrigation is not possible without adequate drainage. Under most soil conditions, a water table will develop if the quantity of wastewater applied greatly exceeds that needed for normal crop growth and leaching. Further discussions of excessive application rates, salinity control, leaching, crop selection, and drainage are presented in Chapters 4, 6, 7, and 8.

Specific Ion Plant Toxicity

Toxicity due to a specific ion occurs when that ion is taken up by the plant and accumulates in the plant in amounts that result in damage or reduced yields. A toxicity problem often accompanies and complicates a salinity, problem although toxicity occasionally occurs even if salinity is low. The ions of most concern in wastewater are sodium, chloride, and boron.

The most prevalent toxicity from the use of reclaimed municipal wastewater is from boron. The source of boron is usually household detergents or discharges from industrial plants. Chloride and sodium also increase during domestic usage, especially where water softeners are used (see Chapter 2). Not all crops are equally sensitive to toxic ions. Information on the sensitivity of crops to boron and chloride is presented in Tables 3-8 and 3-9, respectively.

Table 3-6. Relative salt tolerance of agricultural crops.[a,b]

Tolerant[c]

Fiber, seed and sugar crops
- Barley (*Hordeum vulgare*)
- Cotton (*Gossypium hirsutum*)
- Jojoba (*Simmondsia chinensis*)
- Sugarbeet (*Beta vulgaris*)

Grasses and forage crops
- Alkaligrass, Nuttall (*Puccinellia airoides*)
- Alkali sacaton (*Sporobolus airoides*)
- Bermudagrass (*Cynodon Dactylon*)
- Kallargrass (*Diplachne fusca*)
- Saltgrass, desert (*Distichlis stricta*
- Wheatgrass, fairway crested (*Agropyron cristatum*)
- Wheatgrass, tall (*Agropyron elongatum*)
- Wildrye, Altai (*Elymus angustus*)
- Wildrye, Russian (*Elymus junceus*)

Vegetable crops
- Asparagus (*Asparagus officinalis*)

Fruit and nut crops
- Date Palm (*Phoenix dactylifera*)

Moderately tolerant[c]

Fiber, seed and sugar crops
- Cowpea (*Vigna unguiculata*)
- Oats (*Avena sativa*)
- Rye (*Secale cereale*)
- Safflower (*Carthamus tinctorius*)
- Sorghum (*Sorghum bicolor*)
- Soybean (*Glycine max*)
- Triticale (*X Triticosecale*)
- Wheat (*Triticum aestivum*)
- Wheat, Durum (*Triticum turgidum*)

Grasses and forage crops
- Barley (forage) (*Hordeum vulgare*)
- Brome, mountain (*Bromus marginatus*)
- Canarygrass, reed (*Phalaris arundinacea*)
- Clover, Hubam (*Melotus alba*)
- Clover, sweet (*Melitotus*)
- Fescue, meadow (*Festuca pratensis*)
- Fescue, tall (*Festuca elatior*)
- Hardinggrass (*Phalaris tuberosa*)
- Panicgrass, blue (*Panicum antiodtale*)
- Rape (*Brassica napus*)
- Rescuegrass (*Bromus unioloides*)
- Rhodesgrass (*Chloris Gayana*)
- Ryegrass, Italian (*Lolium multiflorum*)
- Ryegrass, perennial (*Lolium perenne*)
- Sudangrass (*Sorghum sudanense*)
- Trefoil, narrowleaf birdsfoot (*Lotus corniculatus tenuifolium*)
- Trefoil, broadleaf birdsfoot (*Lotus corniculatus arvenis*)
- Wheat (forage) (*Triticum aestivum*)
- Wheatgrass, standard crested (*Agropyron sibiricum*)
- Wheatgrass, intermediate (*Agropyron intermedium*)
- Wheatgrass, slender (*Agropyron trachycaulum*)
- Wheatgrass, western (*Agropyron smithii*)
- Wildrye, beardless (*Elymus triticoides*)
- Wildrye, Canadian (*Elymus canadensis*)

Moderately tolerant[c] (continued)

Vegetable crops
- Artichoke (*Helianthus tuberosus*)
- Beet, red (*Beta vulgaris*)
- Squash, zucchini (*Cucurbita Pepo Melopepo*)

Fruit and nut crops
- Fig (*Ficus carica*)
- Jujuba (*Ziziphus Jujuba*)
- Olive (*Olea europaea*)
- Papaya (*Carica papaya*)
- Pineapple (*Ananas camosus*)
- Pomegranate (*Punica granatum*)

Moderately sensitive[c]

Fiber, seed and sugar crops
- Broadbean (*Vicia Faba*)
- Castorbean (*Ricinus communis*)
- Corn (*Zea Mays*)
- Flax (*Linum usitatissimum*)
- Millet, foxtail (*Setaria italica*)
- Peanut (*Arachis hypogaea*)
- Rice, paddy (*Oryza sativa*)
- Sugarcane (*Saccharum officinarum*)
- Sunflower (*Helianthus annuus*)

Grasses and forage crops
- Alfalfa (*Medicago sativa*)
- Bentgrass (*Agrostis stolonifera palustris*)
- Bluestem, Angleton (*Dichanthium aristatum*)
- Brome, smooth (*Bromus inermis*)
- Buffelgrass (*Cenchrus ciliaris*)
- Burnet (*Poterium Sanguisorba*)
- Clover, alsike (*Trifolium hybridum*)
- Clover, Berseem (*Trifolium alexandrinum*)
- Clover, ladino (*Trifolium repens*)
- Clover, red, (*Trifolium pratense*)
- Clover, strawberry (*Trifolium fragiferum*)
- Clover, white Dutch (*Trifolium repens*)
- Corn (forage) (*Zea Mays*)
- Cowpea (forage) (*Vigna unguiculata*)
- Dallisgrass (*Paspalum dilatatum*)
- Foxtail, meadow (*Alopecurus pratensis*)
- Grama, blue (*Bouteloua gracilis*)
- Lovegrass (*Eragrostis sp.*)
- Milkvetch, Cicer (*Astragalus cicer*)
- Oatgrass, tall (*Arrhenatherum, Danthonia*)
- Oats (forage) (*Avena sativa*)
- Orchardgrass (*Dactylis glomerata*)
- Rye (forage) (*Secale cerale*)
- Sesbania (*Sesbania exaltata*)
- Siratro (*Macroptilium atropurpureum*)
- Sphaerophysa (*Sphaerophysa salsula*)
- Timothy (*Phleum pratense*)
- Trefoil, big (*Lotus uliginosus*)
- Vetch, common (*Vicia angustifolia*)

Vegetable crops
- Broccoli (*Brassica oleracea botrytis*)
- Brussels sprouts (*B. oleracea germmifera*)

Table 3-6. Continued.

Moderately sensitive[c] (continued)

Cabbage (*B. oleracea capitata*)
Cauliflower (*B. oleracea botrytis*)
Celery (*Apium graveolens*)
Corn, sweet (*Zea mays*)
Cucumber (*Cucumis sativus*)
Eggplant (*Solanum Melongena esculentum*)
Kale (*Brassica oleracea acephala*)
Kohlrabi (*B. oleracea gongylode*)
Lettuce (*Lactuca sativa*)
Muskmelon (*Cucumis Melo*)
Pepper (*Capsicum annuum*)
Potato (*Solanum tuberosum*)
Pumpkin (*Cucurbita Pepo Pepo*)
Radish (*Raphanus sativus*)
Spinach (*Spinacia oleracea*)
Squash, scallop (*Cucurbita Pepo Melopepo*)
Sweet potato (*Ipomoea Batatas*)
Tomato (*Lycopersicon Lycopersicum*)
Turnip (*Brassica Rapa*)
Watermelon (*Citrullus lanatus*)

Fruit and Nut Crops
Grape (*Vitis sp.*)

Sensitive[c]

Fiber, seed and sugar crops
Bean (*Phaseolus vulgaris*)
Guayule (*Parthenium argentatum*)
Sesame (*Sesamum indicum*)

Vegetable crops
Bean (*Phaseolus vulgaris*)
Carrot (*Daucus carota*)

Sensitive[c] (continued)

Okra (*Abel moschus esculentus*)
Onion (*Allium Cepa*)
Parsnip (*Pastinaca sativa*)
Pea (*Pisum sativum*)

Fruit and nut crops
Almond (*Prunus Dulcis*)
Apple (*Malus sylvestris*)
Apricot (*Prunus armeniaca*)
Avocado (*Persea americana*)
Blackberry (*Rubus, sp.*)
Boysenberry (*Rubus ursinus*)
Cherimoya (*Annona Cherimola*)
Cherry, sweet (*Prunus avium*)
Cherry, sand (*Prunus Besseyi*)
Currant (*Ribes sp.*)
Gooseberry (*Ribes sp.*)
Grapefruit (*Citrus paradisi*)
Lemon (*Citrus Limon*)
Lime (*Citrus aurantiifolia*)
Loquat (*Eriobotrya japonica*)
Mango (*Mangifera indica*)
Orange (*Citrus sinensis*)
Passion fruit (*Passiflora edulis*)
Peach (*Prunus Persica*)
Pear (*Pyrus communis*)
Persimmon (*Diospyrus virginiana*)
Plum: Prune (*Prunus domestica*)
Pummelo (*Citrus maxima*)
Raspberry (*Rubus idaeus*)
Rose apple (*Syzygium jambos*)
Sapote, white (*Casimiroa edulis*)
Strawberry (*Fragaria sp.*)
Tangerine (*Citrus reticulata*)

a. Data taken from Maas [13].

b. These data serve only as a guideline to the relative tolerances among crops. Absolute tolerances vary with climate, soil conditions, and cultural practices.

c. The relative tolerance ratings are defined by the boundaries in Figure 3-1. Detailed tolerances can be found in Maas [13].

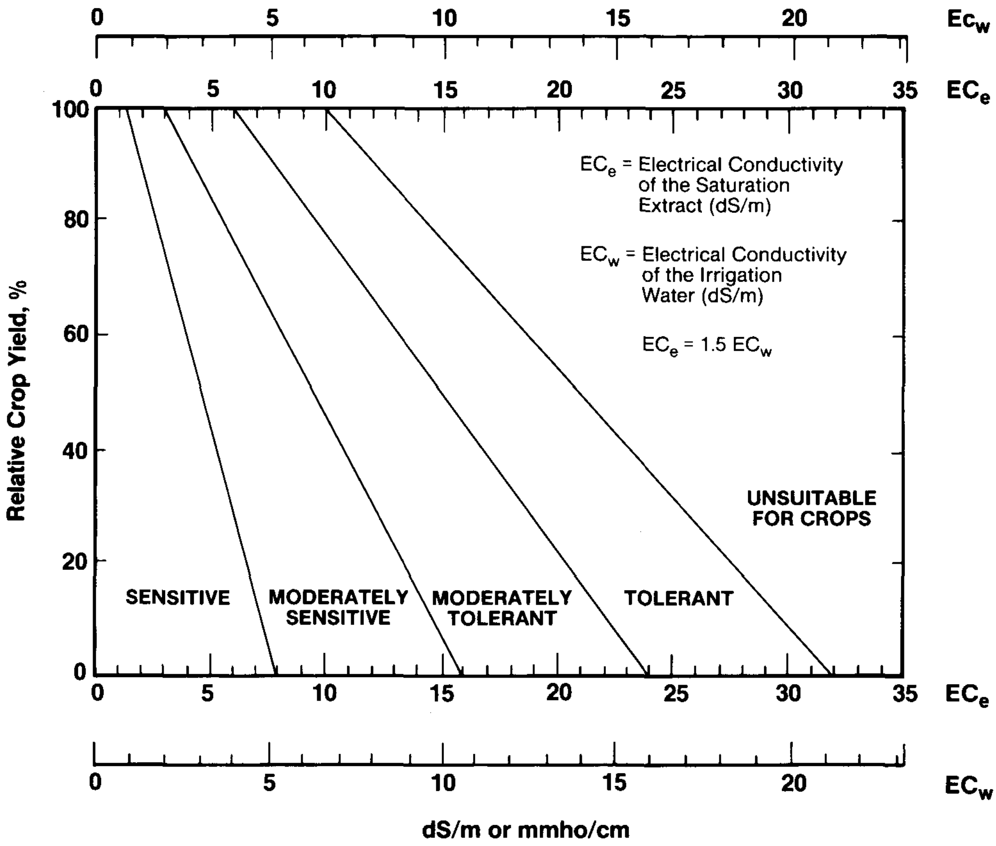

Figure 3-1. Divisions for relative salt tolerance rating of agricultural crops [13].

Table 3-7. Relative salt tolerance of landscape plants.[a,b]

Very sensitive[c]
(Max. EC_w = 0.7-1.4 mmho/cm or dS/m)

Star jasmine (*Trachelospermum jasminoides*)
Pyrenees cotoneaster (*Cotoneaster congestus*)
Oregon grape (*Mahonia Aquifolium*)
Photinia (*Photinia x Fraseri*)

Sensitive[c]
(Max EC_w = 1.4-2.7 mmho/cm or dS/m)

Pineapple guava (*Feiojoa Sellowiana*)
Chinese holly, cv. Burford (*Ilex cornuta*)
Rose, cv. Grenoble (*Rosa sp.*)
Glossy abelia (*Abelia x grandiflora*)
Southern yew (*Podocarpus macrophyllus*)
Tulip tree (*Liriodendron Tulipifera*)
Algerian ivy (*Hedera canariensis*)
Japanese pittosporum (*Pittosporum Tobira*)
Heavenly bamboo (*Nandina domestica*)
Chinese hibiscus (*Hibiscus Rosa-sinensis*)
Laurustinus, cv. Robustum (*Viburnum Tinus*)
Strawberry tree, cv. Compact (*Arbutus Unedo*)
Crape Myrtle (*Lagerstroemia indica*)

Moderately sensitive[c]
Max. EC_w = 2.7-4.0 mmho/cm or dS/m)

Glossy privet (*Ligustrum lucidum*)
Yellow sage (*Lantana camara*)
Orchid tree (*Bauhinia purpurea*)
Southern Magnolia (*Magnolia grandiflora*)
Japanese boxwood (*Buxus microphylla var. japonica*)
Dodonaea, cv. atropurpurea (*Dodonaea Viscosa*)
Oriental arborvitae (*Platycladus orientalis*)

Moderately sensitive[c] (continued)

Thorny elaeagnus (*Elaeagnus pungens*)
Spreading juniper (*Juniperus chinensis*)
Xylosma (*Xylosma congestum*)
Japanese black pine (*Pinus Thunbergiana*)
Indian hawthorn (*Raphiolepis indica*)
Pyracantha, cv. Graberi (*Pyracantha Fortuneana*)
Cherry plum (*Prunes cerasifera*)

Moderately tolerant[c]
(Max. EC_w = 4.0-5.5 mmho/cm or dS/m)

Weeping bottlebrush (*Callistemon viminalis*)
Oleander (*Nerium oleander*)
European fan palm (*Chamaerops humilis*)
Blue dracaena (*Cordyline indivisa*)
Spindle tree, cv. Grandiflora (*Euonymus japonica*)
Rosemary (*Rosmarinus officinalis*)
Aleppo pine (*Pinus halepensis*)
Sweet gum (*Liquidambar Styraciflua*)

Tolerant[c]
(Max. EC_w >5.5 mmho/cm or dS/m)

Brush cherry (*Syzygium paniculatum*)
Ceniza (*Leucophyllum frutescens*)
Natal plum (*Carissa grandiflora*)
Evergreen Pear (*Pyrus kawakamii*)
Bougainvillea (*Bougainvillea spectabilis*)
Italian stone pine (*Pinus pinea*)

Very tolerant[c]
(Max. EC_w >6.8 mmho/cm or dS/m)

White iceplant (*Delosperma alba*)
Rosea iceplant (*Drosanthemum hispidum*)
Purple iceplant (*Lampranthus productus*)
Croceum iceplant (*Hymenocyclus croceus*)

a. Data adapted from Maas [13].

b. Species are listed in order of increasing tolerance based on appearance as well as growth reduction.

c. EC_w = Electrical conductivity of the irrigation water. Salinities exceeding the maximum permissible water salinity (Max. EC_w) may cause leaf burn, loss of leaves, and/or excessive stunting. The maximum values shown were derived from maximum permissible EC_e data by a factor of $EC_e = 1.5EC_w$. This relationship should be valid for normal irrigation practices. The electrical conductivity of the irrigation water can be designated as mmho/cm or dS/m (see Table 3-1).

Table 3-8. Relative boron tolerance of agricultural crops and landscape plants.[a,b]

Agricultural crops

Very sensitive (<0.5 mg/L)

- Lemon (*Citrus limon*)
- Blackberry (*Rubus sp.*)

Sensitive (0.5 - 1.0 mg/L)

- Avocado (*Persea americana*)
- Grapefruit (*Citrus X paradisi*)
- Orange (*Citrus sinensis*)
- Apricot (*Prunus armeniaca*)
- Peach (*Prunus Persica*)
- Cherry (*Prunus avium*)
- Plum (*Prunus domestica*)
- Persimmon (*Diospyros Kaki*)
- Fig, kadota (*Ficus carica*)
- Grape (*Vitis vinifera*)
- Walnut (*Juglans regia*)
- Pecan (*Carya illinoinensis*)
- Cowpea (*Vigna unguiculata*)
- Onion (*Allium Cepa*)
- Garlic (*Allium sativum*)
- Sweet potato (*Ipomea Batatas*)
- Wheat (*Triticum aestivum*)
- Barley (*Hordeum vulgare*)
- Sunflower (*Helianthus annus*)
- Bean, mung (*Vigna radiata*)
- Sesame (*Sesanum indicum*)
- Lupine (*Lupinus Hartwegii*)
- Strawberry (*Fragaria sp.*)
- Artichoke, Jerusalem (*Helianthus tuberosus*)
- Bean, kidney (*Phaseolus vulgaris*)
- Bean, lima (*Phaseolus lunatus*)
- Peanut (*Arachis hypogaea*)

Moderately sensitive (1.0 - 2.0 mg/L)

- Pepper, red (*Capsicum annuum*)
- Pea (*Pisum sativa*)
- Carrot (*Daucus carota*)
- Radish (*Raphanus sativus*)
- Potato (*Solanum tuberosum*)
- Cucumber (*Cucmis sativus*)

Moderately tolerant (2.0-4.0 mg/L)

- Lettuce (*Lactuca sativa*)
- Cabbage (*Brassica oleracea capitata*)
- Celery (*Apium graveolens*)
- Turnip (*Brassica rapa*)
- Bluegrass, Kentucky (*Poa pratensis*)
- Oats (*Avena sativa*)
- Corn (*Zea Mays*)
- Artichoke (*Cynara Scolymus*)
- Tobacco (*Nicotiana Tabacum*)
- Mustard (*Brassica juncea*)
- Clover, sweet (*Melilotus indica*)
- Squash (*Cucurbita Pepo*)
- Muskmelon (*Cucumis melo*)

Tolerant (4.0-6.0 mg/L)

- Sorghum (*Sorghum bicolor*)
- Tomato (*Lycopersicon Lycopersicum*)
- Alfalfa (*Medicago sativa*)
- Vetch, purple (*Vicia benghalensis*)
- Parsley (*Petroselinum crispum*)
- Beet, red (*Beta vulgaris*)
- Sugarbeet (*Beta vulgaris*)

Very tolerant (6.0-15.0 mg/L)

- Cotton (*Gossypium hirsutum*)
- Asparagus (*Asparagus officinalis*)

Ornamentals

Very sensitive (<0.5 mg/L)

- Oregon grape (*Mahonia Aquifolium*)
- Photinia (*Photinia X Fraseri*)
- Xylosma (*Xylosma congestum*)
- Thorny elaeagnus (*Elaeagnus pungens*)
- Laurustinus (*Viburnum Tinus*)
- Wax-leaf privet (*Ligustrum japonicum*)
- Pineapple guava (*Feijoa Sellowiana*)
- Spindle tree (*Euonymus japonica*)
- Japanese pittosporum (*Pittosporum Tobira*)
- Chinese holly (*Ilex cornuta*)
- Juniper (*Juniperus chinensis*)
- Yellow sage (*Lantana Camara*)
- American elm (*Ulmus americana*)

Sensitive (0.5 - 1.0 mg/L)

- Zinnia (*Zinnia elegans*)
- Pansy (*Viola tricolor*)
- Violet (*Viola odorata*)
- Larkspur (*Delphinum sp.*)
- Glossy abelia (*Abelia x grandiflora*)
- Rosemary (*Rosemarinus officinalis*)
- Oriental arborvitae (*Platycladus orientalis*)
- Geranium (*Pelargonium X hortorum*)

Moderately sensitive (1.0 - 2.0 mg/L)

- Gladioli (*Gladiolus sp.*)
- Marigold (*Calendula officinalis*)
- Poinsettia (*Euphorbia pulcherrima*)
- China aster (*Callistephus chinensis*)
- Gardenia (*Gardenia sp.*)
- Southern yew (*Podocarpus macrophyllus*)
- Bruch cherry (*Syzygium paniculatum*)
- Blue dracaena (*Cordyline indivisa*)
- Ceniza (*Leucophyllum frutescens*)

Moderately tolerant (2.0-4.0 mg/L)

- Bottlebrush (*Callistemon citrinus*)
- California poppy (*Eschscholzia californica*)
- Japanese boxwood (*Buxus microphylla*)
- Oleander (*Nerium Oleander*)
- Chinese hibiscus (*Hibiscus Rosa-sinensis*)
- Sweetpea (*Lathyrus odoratus*)
- Carnation (*Dianthus Caryophyllus*)

Tolerant (6.0-8.0 mg/L)

- Indian hawthorn (*Raphiolepis indica*)
- Natal plum (*Carissa grandiflora*)
- Oxalis (*Oxalis Bowiei*)

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a. Data taken from Maas [13].

b. Maximum concentrations tolerated in soil water without yield or vegetative growth reductions. Boron tolerances vary depending upon climate soil conditions and crop varieties. Maximum concentrations tolerated in the applied irrigation water are approximately equal to these values for soil-water or slightly less.

Table 3-9. Chloride tolerance of some fruit crop cultivars and rootstocks.[a]

Crop	Rootstock or cultivar	Maximum permissible Cl^- in water without leaf injury[b,c] (mg/L)
	Rootstocks	
Avocado (*Persea americana*)	West Indian	180
	Guatemalan	145
	Mexican	110
Citrus (*Citrus spp.*)	Sunki mandarin, grapefruit Cleopatra mandarin, Rangpur lime	600
	Sampson tangelo, rough lemon, sour orange, Ponkan mandarin	355
	Citrumelo 4475, trifolate orange, Cuban shaddock, Calamondin, sweet orange, Savage citrange, Rusk citrange, Troyer citrange	250
Grape (*Vitis spp.*)	Salt Creek, 1613-3	960
	Dog ridge	710
Stone fruit (*Prunus spp.*)	Marianna	600
	Lovell, Shalil	250
	Yunnan	180
	Cultivars	
Berries (*Rubus spp.*)	Boysenberry	250
	Olallie blackberry	250
	Indian Summer raspberry	110
Grape (*Vitis spp.*)	Thompson seedless, Perlette	460
	Cardinal, black rose	250
Strawberry (*Fragaria spp.*)	Lassen	180
	Shasta	110

a. Data are adapted from Maas [13].

b. For some crops, the concentrations given may exceed the overall salinity tolerance of that crop and cause some yield reduction before chloride ion toxicities. Values given are for the maximum concentration in the irrigation water. The values were derived from saturation extract data (EC_e) by the following relationship: saturation extraction concentration = 1.5 water concentration.

c. The maximum permissible values apply only to surface irrigated crops. Sprinkler irrigation may cause excessive leaf burn at values far below these (see Table 3-10).

For sensitive crops, toxicity is difficult to correct short of changing the crop or the water supply. The problem is accentuated by severe (hot) climatic conditions. Symptoms appear on almost any crop if concentrations are high enough. With sprinkler irrigation, sodium and/or chloride frequently accumulates by direct adsorption through the leaves that are moistened. Such toxicity occurs at chloride or sodium concentrations that are much lower than toxicity caused by surface irrigation (Table 3-9). Compare Table 3-9 with Table 3-10, which gives the relative susceptibility of selected crops to leaf injury when using overhead sprinkler irrigation. Sprinkler irrigation during windy periods or periods of high temperature and low humidity increases the likelihood of sodium or chloride toxicity. Night irrigation to benefit from lower temperatures and higher humidity greatly reduces and sometimes eliminates the toxicity associated with overhead sprinkling. Chapter 7 discusses these and other management alternatives.

Soil Permeability (Infiltration)

In addition to their effects on the plant, sodium salts in irrigation water may affect soil structure and reduce the rate at which water moves into the soil as well as reduce soil aeration. If the infiltration rate is greatly reduced, it may be impossible to supply the crop or landscape plant with enough water for good growth. Normally other secondary problems--crusting, excessive weed growth, and oxygen deficiencies--are evident at the same time, resulting from poor soil structure and surface waterlogging. Reclaimed-wastewater irrigation systems are frequently located on less desirable soils or those already having soil permeability and management problems, which increases the probability of a problem.

A permeability problem usually occurs in the surface few inches of the soil and is mainly related to a relatively high sodium or very low calcium content in this zone or in the applied water. Maintaining good soil structure under California conditions means maintaining adequate levels of calcium in soil or water. A low soil calcium content can be caused by water of very low salinity, which dissolves and leaches the calcium, or caused by a high sodium water,

Table 3-10. Relative tolerance of selected crops to foliar injury from saline water applied by sprinklers.[a,b]

Na or Cl concentrations (meq/L)[c] causing foliar injury[d]			
<5	5-10	10-20	>20
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Corn	Sugarbeet
Plum	Tomato	Cucumber	Sunflower
		Safflower	
		Sesame	
		Sorghum	

(a) Data taken from Maas [13].

(b) Susceptibility based on direct adsorption of salts through the leaves.

(c) The concentration of Na or Cl in meq/L can be determined from mg/L by dividing mg/L by the equivalent weight for Na (23) or Cl (35.5). (meq/L = mg/L/equivalent weight).

(d) Foliar injury is influenced by cultural and environmental conditions. These data are presented only as general guidelines for daytime sprinkler irrigation.

which adds excessive amounts of sodium relative to calcium. The permeability guidelines in Table 3-4 incorporate the potential effect of both salinity and sodium on soil permeability. Water of high salinity increases permeability and at least partially offsets an expected permeability problem predicted by the SAR alone. At a given SAR, the infiltration rate increases as salinity increases or decreases as salinity decreases. Therefore, SAR and EC_w should be used in combination to evaluate the potential permeability problem.

Reclaimed municipal wastewaters are normally high enough in both salt and calcium, and there is little concern for the water dissolving and leaching too much calcium from the surface soil. However, reclaimed wastewaters are relatively high in sodium; the resulting high SAR is a major concern in planning wastewater reuse projects. Soil management techniques are available (Chapter 7) to mitigate permeability problems and allow successful use of waters with a high SAR, but often these practices must be used continuously in order to avoid loss of soil structure. These techniques, if adopted, will promote better water penetration and help avoid vector problems (e.g., mosquitos) often associated with water standing or ponding too long on the soil surface.

Potential permeability problems that are predicted by the guidelines in Table 3-4 using the EC_w in combination with SAR may turn out to be more severe or less severe than predicted. This can be due to changes in calcium content of the applied water following irrigation at which time "applied water" becomes "soil-water". Changes in calcium are caused by precipitation from the water or dissolution from the soil as influenced by several soil-water characteristics: salinity, bicarbonate content relative to calcium, and carbon dioxide content.

An adjusted sodium adsorption ratio (adj R_{Na}) as calculated from procedures outlined in Table 3-2 evaluates these effects and more correctly predicts the effective SAR for certain waters including sewage effluents and other wastewaters. This adj R_{Na} may be used in place of SAR in the "Permeability" guidelines of Table 3-4 to more correctly predict the potential problem.

Trace Elements

The values in Table 3-5 give the suggested maximum concentrations of trace elements in water that can be used for long-term irrigation. None of the elements listed in Table 3-5 cause toxicities at the levels given, and the water should be considered safe for continuous irrigation of all crops on all soil types when these values are not exceeded. This does not mean that if the suggested limit is exceeded that phytotoxicity will occur. Most of the elements listed are readily fixed or tied up in soil and accumulate with time. Repeated applications in excess of the level suggested would eventually increase the soil concentration to a level where phytotoxicity might occur. The intent of the suggested limits in Table 3-5 is to ensure that the site where reclaimed wastewater is used can be used for all potential crops in the future. It is recommended that the values in Table 3-5 be considered the maximum long-term average concentrations based upon normal irrigation applications. It may be necessary over the short-term to exceed either the maximum concentration or the normal water application rate; an adjustment in future concentration or water application rate then needs to be made. Chapter 13 discusses the long-term soil loading rates in more detail. It is also recommended that periodic soil and water monitoring be conducted to estimate the rate of accumulation and to help plan for future uses of the irrigated area.

Typical concentrations of trace elements found in the effluent from several small and medium sized wastewater treatment plants in California are given in Table 3-11. The concentrations show little potential problem from trace element accumulation at any site. Such small- and medium-sized communities have the greatest potential for wastewater reclamation and reuse, because available cropland is usually close by, thereby reducing the cost of transporting the wastewater. In addition, these communities are not highly industrialized, and in almost all instances, trace element concentrations in the reclaimed wastewater are below those set as standards for California drinking water and are far below the maximum long-term averages for irrigation given in Table 3-5. Table 3-12 shows the estimated total weight of each trace element applied over a

Table 3-11. Trace element concentrations in municipal wastewater treatment plant effluent (mg/L) from selected cities in California.[a]

Trace element	Irrigation water[b] standards	Drinking water standards[b]	City of Santa Rosa[c]	Orange County SD[d]	City of Hollister[e]	City of Modesto[f]	City of Fresno[f]	Selma Kingsburg Fowler SD[f]	Sacramento Regional Plant[g]	East Bay MUD[h]	City of San Bernardino[h]	Chino Basin MUD[h]	City of San Francisco[h]	City of Woodland[f]
Ag (silver)	-	0.05		0.004	<0.002		<0.001	<0.05	0.004	0.0008	<0.01	<0.005	0.005	
As (arsenic)	5.0	0.05	0.003	0.002	<0.01	<0.01	0.002	<0.01	0.0026	0.008	<0.01	<0.001	0.003	<0.05
B (boron)	0.7	-	0.53	0.62		<0.05		0.5						
Ba (barium)	-	1.0		0.082	0.13		0.005				<0.05	<0.001		
Be (beryllium)	0.1	-				<0.01	<0.001	<0.02	<0.01					<0.005
Cd (cadmium)	0.01	0.01	0.006	0.009	<0.004	<0.001	<0.001	<0.005	<0.01	0.0008	<0.005	0.006	0.005	<0.03
Co (cobalt)	0.05	-	<0.001		<0.008	<0.01		<0.1			<0.025	<0.001		
Cr (chromium)	0.1	0.05	0.003	0.204[i]	<0.014	0.066[i]	<0.001	0.002	0.015	0.02	<0.01	0.01	0.020	<0.01
Cu (copper)	0.2	0.1	0.004	0.291[i]	0.034	0.05	0.013	<0.01	0.026	<0.02	0.08	0.015	0.083	<0.05
Fe (iron)	5.0	0.3	0.21	0.19	0.39[i]	0.25					0.17	<0.05		0.30
Hg (mercury)	-	0.002		<0.001	<0.001		0.0003	<0.0004	0.0006	<0.0002	<0.001	<0.001	0.0020	<0.001
Mn (manganese)	0.2	0.05	0.068[i]	0.038	0.070[i]	0.05		0.04			0.03	0.01		
Ni (nickel)	0.2	-	0.04		0.051	0.05	0.030	<0.025	0.08	0.032			0.083	<0.04
Pb (lead)	5.0	0.05	0.017	0.035	0.054[i]	<0.005	0.050	<0.001	0.04	0.006	<0.01	0.02	0.07[i]	<0.04
Se (selenium)	0.02	0.01	0.001	0.007	<0.001	<0.005	0.003		0.0002		<0.001	<0.001		<0.005
Zn (zinc)	2.0	5.0	0.06	0.308	0.048	<0.01	0.041	<0.04	0.06	0.08	<0.075	0.022	0.22	0.34

a. Values presented with a <sign signify that the element may or may not be present at a concentration below the level of detection. The level of detection is represented by the value given when preceded by a < sign.

b. Recommended maximum concentrations in drinking water as defined by the California Administrative Code [14] and irrigation water (see Table 3-4).

c. Bain and Esmaili [15].

d. Argo [16].

e. Pound et al. [17].

f. Data gathered by the City or District during development of their Industrial Pretreatment Program.

g. Sacramento Area Consultants [18].

h. Regional Water Quality Control Board Monitoring Report Files, 1982-83.

i. Those values underlined exceed the California Drinking Water Standards, but only the values for Copper (Cu) and Chromium (Cr) for the Orange County SD would exceed that normally considered safe for long-term irrigation (see Table 3-4).

Table 3-12. Estimated mass application of trace elements to soil after 20 years of irrigation using a municipal wastewater typical of Hollister, California.

Element	Average metal concentration[a] (mg/L)	Element applied after 20 yrs.[b] (kg/ha)	Typical background levels in selected California soils[c,d] (kg/ha)	Increase (%)
Ag (silver)	<0.008	<1.92	-	-
As (arsenic)	<0.01	<2.4	12	<20
Ba (barium)	<0.13	<31.2	1,000	<3
Cd (cadmium)	<0.004	<0.96	1.53	<62
Co (cobalt)	<0.008	<1.92	16	<12
Cr (chromium)	<0.014	<3.36	69.3	<5
Cu (copper)	0.034	8.16	65.7	12
Fe (iron)	0.39	93.6	75,000	0.1
Hg (mercury)	<0.001	<0.24	-	-
Mn (manganese)	0.070	16.8	1,530	1
Ni (nickel)	0.051	12.24	63.3	19
Pb (lead)	0.054	12.96	74.7	17
Se (selenium)	<0.001	<0.24	0.4	<60
Zn (zinc)	0.048	11.52	272	4

a. Data taken from Pound et al. [17].

b. Based on an annual effluent application rate of 4 ft/year (1.2 m/year) for 20 years.

c. Based on data from 26 selected California soils (See Appendix I). Data for As, Ba, Co, and Se were adapted from Page [19].

d. Data presented for typical background levels were determined by 4N HNO_3 extraction; therefore, the procedure may not have extracted all the metal in the soil, but the procedure is commonly used for a total metal analysis.

simulated 20-year application period at Hollister, California. Similar estimations should be made for each reclaimed wastewater irrigation site.

Nutrients

The nutrients in reclaimed municipal wastewaters provide fertilizer benefits to crop or landscape production but in certain instances are in excess of plant needs and cause problems related to excessive vegetative growth, delayed or uneven maturity, or reduced quality. Make a periodic check to estimate the amount of nutrients being applied. These amounts should then be included as part of the fertilization program. Nutrients occurring in quantities important to California agriculture and landscape management include nitrogen and phosphorus and occasionally potassium, zinc, boron, and sulfur. The most beneficial and the most frequently excessive nutrient is nitrogen. Guidelines in Table 3-4 give interpretive criteria. The following discussion covers the nutrients listed above (Chapter 12 gives a more detailed discussion).

Nitrogen

The total nitrogen content of municipal wastewater following secondary treatment ranges from 20 to 60 mg/L, but the nitrogen concentration as well as the form of nitrogen (NH_4-N, NO_3-N, organic-N) depends on the degree and type of treatment that is given (see Chapter 2). Table 3-13 shows the variation in total nitrogen and the forms of nitrogen that occur in effluent from a few California wastewater treatment plants. For example, an effluent from a secondary treatment plant contains very little nitrogen in the form of nitrate unless the plant is operated in a nitrification mode. The total nitrogen may exceed this by 10-fold or more (Table 3-12). The guidelines given in Table 3-4 are for total nitrogen regardless of the form.

The nitrogen in reclaimed wastewater that reaches the field in irrigation water is essentially equal to fertilizer nitrogen but is not easily regulated. At each irrigation, nitrogen is applied along with the water and fertilizes the crop. This is beneficial in the

Table 3-13. Reported concentrations of nitrogen (N), phosphorus (P), and potassium (K) in municipal wastewater from selected wastewater treatment plants in California.[a]

Treatment plant	NH_4-N	NO_3-N	Organic-N	Total-N	Total-P	K
			(mg/L)			
			Untreated wastewater			
City of Davis[b]	35.6	0	7.8	43.4	-	-
City of Long Beach	28.7	<1	12.9	41.6	34.6	19
City of Pomona	20.6	<1	14.0	34.6	28.3	13
			Primary treatment			
City of Davis[b]	26.2	0	8.5	34.7	-	-
City of Ventura (Seaside)	25.0	0	10.0	35.0	10.0	18
CSDLAC Joint Plant (Los Angeles County)	39.5	0	14.9	54.4[c]	11.2	19
			Secondary treatment (activated sludge)			
City of Santa Rosa	13.0	0.2	5.8[c]	19.0	18.3	10
City of Palo Alto	24.0	0.4	3.3	27.7	6.2	11
			Secondary treatment (oxidation ponds)			
City of Davis[b]	1.0	5.0	13.0	-	-	
Napa Sanitation District	1.5	2.2	10.7	14.4	5.5	27
City of Modesto	-	2.0	-	28.9	12.7	34
American Canyon CWD	6.1	1.2	11.0	18.3	8.6	20
Jamestown Sanitation Dist.	<1.0	1.0	10.0	11.6	7.3	10
			Advanced wastewater treatment			
Dublin-San Ramon Ser. Dist.	0.1	19.0	0.2	19.3	28.5	-
City of Livermore	1.0	21.3	2.6	24.9	16.5	-
City of Pomona	11.4	3.3	1.3	16.0	21.7	12
Simi Valley CSD	16.6	0.4	2.3	19.3	-	-

a. Data adapted from the plant performance data presented in Chapter 2 of this manual and from actual treatment plant performance data derived from the records of the individual treatment plants.

b. Data for the City of Davis show the change in total nitrogen that takes place during wastewater treatment and storage.

c. Values presented are estimates.

early stages of growth but much less beneficial towards maturity. In some cases, nitrogen is excessive, stimulates excessive vegetative growth, and may delay maturity or reduce crop quality. In other cases, too little nitrogen is present and supplemental fertilizer nitrogen is needed for satisfactory crop yields. See Chapter 12 for a discussion of the fate of nitrogen applied to soil.

Phosphorus

Phosphorus is also needed by all plants. Phosphorus in effluent from secondary treatment systems varies from 6 to 15 mg/L (15-35 mg/L P_2O_5) unless removal has been accomplished during treatment. On arrival at the field for irrigation, the phosphorus content in reclaimed wastewater may be much less and is usually too little during the early growth period to materially affect crop yield. It gradually builds up the soil phosphorus, however, and reduces the need in future years for supplemental phosphorus fertilizers. Excessive phosphorus has not been a problem, and no guideline value is given for its evaluation, but checks of the reclaimed wastewater should be made in conjunction with soil testing for fertilization planning. Phosphorus soil reactions are discussed in Chapter 12.

Potassium

Most California soils are adequately supplied with potassium, and the potassium in municipal effluent does not usually improve yields or crop quality. The range of potassium in secondary effluent is 10-30 mg/L (12-36 mg/L K_2O) (see Table 3-13).

Zinc

Almost all wastewater effluent contains enough zinc to correct soil deficiencies within 1-3 years. The zinc is considered beneficial to deficient soils, but the maximum values given in Table 3-5 should not be exceeded.

Sulfur

In a few instances, particularly in areas with higher rainfall (>20 inches [50.8 cm]) in the Sierra Nevada and North Coast, sulfur deficiencies frequently reduce yields of crops and rangeland. Sufficient sulfur is present in reclaimed municipal wastewater to correct sulfur deficiencies.

Boron

Reclaimed municipal wastewater contains enough boron to correct any boron deficiencies in soils. Of greater concern is an excess of boron that may reduce yields. Excesses are discussed under the section entitled "Specific Ion Plant Toxicity."

Miscellaneous Problems

Occasional problems of abnormal pH, corrosion of pipelines and equipment, irrigation water system clogging, and high residual chlorine occur when using reclaimed wastewater is used. These problems need to be evaluated case by case.

Water pH is seldom a direct problem by itself, but pH outside the normal range (6.5-8.5) is a good indicator of an abnormal water or one with a toxic ion present. If an abnormal pH is found, this should be a warning that the water needs further evaluation and possibly correction with amendments.

A corrosion problem may occur in either metal or concrete pipelines due to a low pH, to high or free carbon dioxide, or in some cases to a secondary effect of a drop in dissolved oxygen caused by higher than normal organic loading of the treated wastewater. The dissolved oxygen problem results in the formation of hydrogen sulfide gas, which is common where primary effluent is transported over long distances in a closed pipeline or where there is no way of draining the wastewater from the distribution line following irrigation. Corrosion problems are troublesome if metal gates or pipes are used. The corrosion problems do not commonly occur with well stabilized secondary effluent.

Clogging problems with sprinkler and drip irrigation systems have been reported. Growths (slimes, bacteria, etc.) in the sprinkler head, emitter orifice, or supply line cause plugging, as do heavy concentrations of algae and suspended solids. The most frequent clogging problems occur with drip irrigation systems. Such systems are often considered ideal, as they are totally closed systems and avoid the problems of worker safety and drift control. See Chapter 8 for the advantages and disadvantages of the various irrigation systems. Higher than normal suspended solids and nutrient levels in treated wastewater may require filtration just before use, which makes management of a drip irrigation system using wastewater difficult. Guidelines are presented in Table 3-14 to help evaluate the suitability of a water for use through a drip irrigation system. The important point to remember in using these drip irrigation guidelines is that they are only broad indicators, and other factors such as temperature, sunlight, emitter types, and flow rates greatly alter the degree of problem expected. A combination of two or more factors is more difficult to solve and affects irrigation efficiency more severely than a single factor acting alone. The more complex the problem, the more difficult it becomes to develop an economical management scheme. It is likely that a drip irrigation system compatible with wastewater use will become available as new emitter designs are tried.

Excessive residual chlorine in municipal effluent causes plant damage when sprinkers are used if the high chlorine residual exists at the time the effluent is sprinkled on plant foliage. As free chlorine (Cl_2) is highly reactive and unstable in water, a high chlorine residual rapidly dissipates if the treated wastewater is placed in an open storage pond for more than a few hours.

A residual chlorine less than 1 mg/L should not affect plant foliage, but where Cl_2 residual is in excess of 5 mg/L, severe plant damage can occur [Branson-personal communication.] The severity or likelihood of plant damage increases as the concentration increases above 1 mg/L. Guidelines for chlorine residual are presented in Table 3-4, and these should be used as a warning that potential problems may occur. More experience is needed before better definitive values can be given. Most treated wastewater reuse schemes will not encounter this problem if an intermediate storage facility is used, but care is needed during any period where the storage facility is by-passed for direct irrigation from the treatment plant.

Table 3-14. Plugging potential of irrigation water used in drip irrigation systems [20].

Type of problem	Potential restrictions on use		
	Little	Slight to moderate	Severe
Physical			
Suspended solids (mg/L)	<50	50 - 100	>100
Chemical			
pH	<7.0	7.0 - 8.0	>8.0
Dissolved solids (mg/L)	<500	500 - 2,000	>2,000
Manganese (mg/L)[a]	<0.1	0.1 - 1.5	>1.5
Iron (mg/L)[b]	<0.1	0.1 - 1.5	>1.5
Hydrogen sulfide (mg/L)	<0.5	0.5 - 2.0	>2.0
Biological			
Bacterial populations (maximum number/mL)	<10,000	10,000 - 50,000	>50,000

a. While restrictions in use of drip irrigation systems may not occur at these manganese values, plant toxicities may occur at lower values (see Table 3-5).

b. Iron concentrations >5.0 mg/L may cause nutritional imbalances in certain crops (see Table 3-5).

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CHAPTER 4
SITE CHARACTERISTICS
R. W. Crites

INTRODUCTION

The characteristics of the site to be used for agricultural or landscape irrigation with reclaimed municipal wastewater can affect the planning, design, and management of the system. In this chapter, the important characteristics affecting site evaluation and field investigations for determining infiltration rate and soil permeability are described. The effects of vegetation, wastewater loadings, and management on infiltration rates are discussed.

SITE EVALUATION

Important factors in site evaluation include topography, soils, geology, groundwater, land use, and climate. Other variables that affect system planning include wastewater characteristics (Chapter 2), water-quality criteria (Chapter 3), agricultural practices in the area, the selected crop (Chapter 6), and water rights (Chapter 11). Crop water use is discussed in Chapter 5. Agricultural practices can affect site selection if the area is dominated by vegetable cropping or other high-value specialty crops.

Topography

Topographic features of importance in site evaluation are slope, relief, and susceptibility to flooding. Slope and relief can be determined from topographic maps such as U.S. Geological Service (USGS) 7.5-minute maps (scale 1:24,000) or 15-minute maps (scale 1:62,500). In addition, slope categories are included on detailed soils maps published by the Soil Conservation Service (SCS).

The topography of the land surrounding the potential site should also be evaluated for its potential to (1) add stormwater runoff to the site, (2) back up drainage water onto the site, (3) cause groundwater seepage onto the site, and (4) provide relief drainage [1].

Slope and Relief

Excessive slope (feet of grade difference per 100 ft expressed as %) is an undesirable characteristic for wastewater-irrigated sites because (1) it increases the amount of runoff and erosion that will occur, (2) it may lead to unstable soil conditions when the soil is saturated, (3) it makes crop cultivation difficult or even impossible, and (4) it is usually expensive to irrigate. Criteria for maximum slope depend on the type of cropping system. For cultivated agriculture, a maximum slope of 15% is usually recommended. Crops that do not require cultivation, such as pasture, can be adapted to slopes of 15% to 20% or more, depending on runoff constraints. Sprinkler irrigation of woodlands with slopes of 15% to 30% has been studied [2], and successful operations on wooded slopes up to 40% have been reported [3].

Relief is the difference in elevation between one part of the irrigation site and another. The primary concern about relief is its effect on pumping and distributing effluent on the site. It may cost more, for example, to pump effluent to a nearby site that has substantial relief than to construct a gravity conveyance system to a more distant site.

Susceptibility to Flooding

Location of wastewater irrigation systems within a flood plain can be either an asset or a liability, depending on the approach taken to planning and design. Flood-prone areas may be undesirable because of the highly variable drainage characteristics usually encountered and because of potential flood damage to the physical components of the treatment system. On the other hand, flood plains, alluvial deposits, and delta formations may be the only deep soils available in the area. With careful design and choice of application techniques, a wastewater irrigation system can be an integral part of a flood-plain-management plan. The flooding hazard of a potential site should be evaluated with respect to both the severity of floods that could occur and the extent of the area flooded.

The extent of flood-protection measures built into a wastewater irrigation system will depend on local conditions. In some cases, it may be preferred to allow the site to flood as needed and provide the protection through offsite storage. Also, flood plains are generally unacceptable for construction of dwellings or commercial buildings, offering an opportunity for imaginative uses of wastewater irrigation systems. Crops can be grown in flood plains if the infrequency of floods makes it economical to farm.

Description of severe floods that have occurred in the United States and summaries of all notable floods of each year are published as USGS Water Supply Papers. Maps of certain localities showing the area inundated in past floods are published as Hydrologic Investigation Atlases by the USGS. More recent maps of flood-prone areas have been produced by the USGS in many areas of the country as part of the "Uniform National Program for Managing Flood Losses." The maps are based on standard 7.5-minute USGS topographic sheets. By means of an overprint in black and white, they identify those areas that have a 1 in 100 chance of being inundated in any given year. Other detailed flood information is usually available from local offices of the U.S. Army Corps of Engineers and from the flood-control districts that deal with such problems first-hand.

Soils

The soil types at a potential site should be identified, and physical, hydraulic, and chemical characteristics of each soil type should be defined. Important physical characteristics include texture, structure, and soil depth. Important hydraulic characteristics are infiltration rate and permeability. Soil chemical properties of importance are pH, electrical conductivity, exchangeable sodium percentage, available phosphorus, organic matter, and, in some areas, boron content.

Soil Surveys

Soil surveys are usually available from the SCS. Soil surveys normally contain maps showing soil series boundaries and textures to a depth of about 5 ft (1.5 m). The scale of these maps ranges from 1:20,000 to 1:24,000 with most recent surveys having a scale of 1:24,000. In a survey, limited information on chemical properties, grades, drainage, erosion potential, general suitability for locally grown crops, and interpretive and management information is provided. In some areas, published surveys are not available or exist only as detailed reports with maps ranging in scale from 1:100,000 to 1:250,000.

Soils with profiles nearly alike make up a soil series. Except for allowable differences in texture of the surface layer or of the underlying substratum, all the soils of a series have major horizons (layers) that are similar in composition, thickness, and arrangement in the profile. A soil series commonly is named for a town or geographic feature near the place where a soil of that series was first observed and mapped.

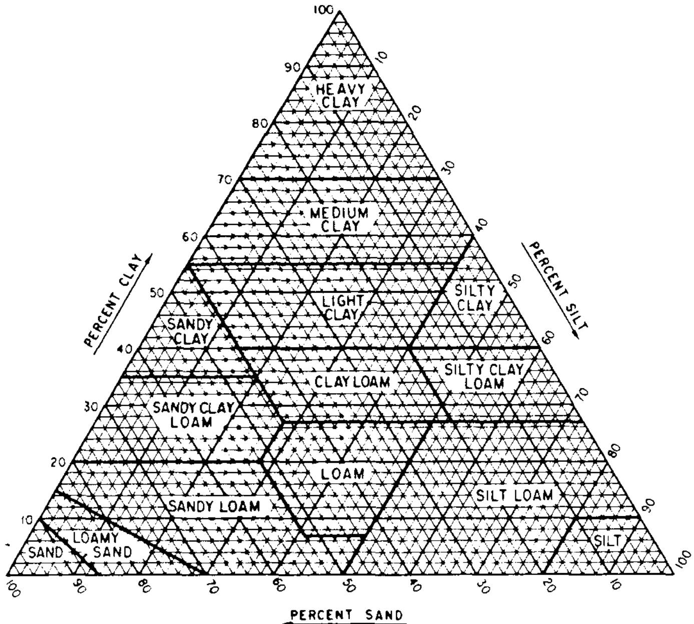
Soils of one series can differ in texture of the surface horizon or in the underlying substratum and in slope, erosion, stoniness, salinity, or other characteristics. On the basis of such differences, a soil series is divided into phases. The name of the soil phase or type commonly indicates a feature that affects use or management.

A map of California indicating areas with detailed soil surveys and areas where soil surveys are currently underway is available from State Conservationist, Soil Conservation Service, 2828 Chiles Road, Davis CA 95616.

Soil Physical Characteristics

The physical properties of texture and structure are important because of their effect on hydraulic properties. Soil textural classes are defined on the basis of the relative percentage of the three classes of particle size: sand, silt, and clay. Sand particles range in size from 2.0 to 0.05 mm; silt particles range from 0.05 mm to 0.002 mm; and particles smaller than 0.002 mm are clay according to the USDA classification system. Textural class can be assigned from particle size distribution using Figure 4-1 or can be estimated by soil scientists in the field.

Because fine-textured soils generally do not drain well and retain large percentages of water for long periods, crop management is more difficult than with more freely drained soils such as loamy soils. Medium-textured soils exhibit the best balance for wastewater



TEXTURAL CLASSES

TEXTURE		SAND %	SILT %	CLAY %
SAND	(S)	85 to 100	0 to 15	0 to 10
LOAMY SAND	(LS)	70 to 90	0 to 20	0 to 15
SANDY LOAM	(SL)	43 to 85	0 to 50	0 to 20
LOAM	(L)	23 to 52	28 to 50	7 to 27
SILT LOAM	(SiL)	0 to 50	50 to 100	0 to 27
SANDY CLAY LOAM	(SCL)	45 to 80	0 to 28	20 to 35
CLAY LOAM	(CL)	20 to 45	15 to 53	27 to 40
SILTY CLAY LOAM	(SiCL)	0 to 20	40 to 73	27 to 40
SANDY CLAY	(SC)	45 to 65	0 to 20	35 to 55
SILT	(Si)	0 to 20	80 to 100	0 to 12
SILTY CLAY	(SiC)	0 to 20	40 to 60	40 to 60
CLAY	(C)	0 to 46	0 to 40	40 to 100

BASIC TEXTURAL CLASS MODIFYING TERMS

SAND

Diameter, millimeter	U.S. Standard sieve numbers	Term	
0.05 to 0.10	300 to 140	Very fine sand	(VFS)
0.10 to 0.25	140 to 60	Fine sand	(FS)
0.25 to 0.50	60 to 35	Medium sand	(S)
0.50 to 1.00	35 to 18	Coarse sand	(CsS)
1.00 to 2.00	18 to 10	Very coarse sand	(VCsS)

GRAVEL

Content, Percent	Term	
20 to 50	Gravelly	(Gr)
50 to 90	Very Gravelly	(VGr)

Coarse sand: 25% or more VCsS and less than 50% of any other grade of sand.
Sand: 25% or more VCsS, CsS, and S, and less than 50% of F or VFS.
Fine sand: 50% or more FS and less than 25% of VCsS, CsS, and S and less than 50% of VFS
Very fine sand: 50% or more VFS

Figure 4-1. Soil triangle of the basic soil textural classes [4] renovation and drainage. Loamy (medium textured) soils are generally best suited for irrigation systems. Coarse-textured soils (sandy soils) can accept large quantities of water and do not retain moisture very long. This feature is important for crops that cannot withstand prolonged submergence or saturated root zones.

Soil structure refers to the aggregation of individual soil particles. If these aggregates resist disintegration when the soil is wetted or tilled, it is well structured. The large pores in well-structured soils conduct water and air, making well-structured soils desirable for infiltration. Structure is not usually evaluated quantitatively during site investigations.

Adequate soil depth is important for root development, for retention of wastewater components on soil particles, and for bacterial action. Plant roots can extract water at depths from the soil surface of 1 ft to 9 ft (0.3 to 2.7 m) or more. Retention of wastewater components, such as phosphorus and viruses, is a function of residence time of wastewater in the soil and the degree of contact between soil colloids and the wastewater components. For wastewater irrigation sites, a soil depth of 2 to 3 ft (0.6 to 0.9 m) is generally adequate for wastewater treatment. For deep-rooted crops, greater soil depths may be required.

Hydraulic Characteristics

Both the infiltration rate and saturated permeability are important design parameters for reclaimed wastewater irrigation systems. The infiltration rate is the rate at which water enters the soil surface when excess water is present. The rate for a specific soil varies inversely with the water content of the soil profile and approaches a steady-state minimum value as the profile reaches saturation. The minimum infiltration rate at saturation is the principal parameter used in determining the design application rate for sprinkler distribution systems. The design sprinkler application rate is set at less than the minimum infiltration rate to avoid surface runoff (see Chapter 8). Infiltration rate measurements, described later in this chapter, can also be used to estimate the saturated vertical permeability of subsurface soil horizons as well as the surface horizon.

Saturated, vertical soil permeability of a soil horizon (used synonymously with hydraulic conductivity in this manual) is equal to the rate at which water percolates in vertically through the soil horizon under saturated conditions. (The term hydraulic conductivity is the correct term by current definition, but, because the term permeability has been used in this context throughout many SCS soil surveys, permeability is also used in this manual to avoid confusion.) Saturated permeability can be estimated from the range of values given in the SCS survey or it can be measured in the field. The SCS has defined permeability classes for soil as shown in Table 4-1. Different soil horizons vary in permeability, but the important value for design is the lowest permeability in the soil profile. This minimum permeability value is used in determining the design hydraulic loading rates for Type II irrigation systems (see Chapter 8).

Table 4-1. Permeability classes for saturated soil.

Soil permeability (inch/hour)	Class
<0.06	Very slow
0.06 to 0.2	Slow
0.2 to 0.6	Moderately slow
0.6 to 2.0	Moderate
2.0 to 6.0	Moderately rapid
6.0 to 20	Rapid
>20	Very rapid

The SCS soil surveys generally include the expected permeability range for each horizon in the soil profile. This information is sufficient in most cases for preliminary planning of irrigation systems. In some cases, it may be advisable to measure the permeability of the limiting soil horizon or the infiltration rate of the surface soil before designing the system. Recommended field investigation procedures are discussed later in the chapter.

Soil Chemistry

Soil chemical properties can affect both permeability and crop growth potential. For site evaluation, the pH, electrical conductivity (EC), and exchangeable sodium percentage (ESP) represent sufficient information in most cases. In some cases the cation exchange capacity (CEC), available phosphorus, organic matter, or boron content may also be important. Generally it is not necessary to measure soil chemical properties during planning unless there is the potential for high sodium levels in the soil or if boron-sensitive and other salt-sensitive crops are being contemplated for planting.

The SCS survey usually includes data on soil pH and occasionally on CEC and EC. If there is potential for a high sodium content of the soil or of the wastewater (discussed in Chapter 7), the ESP levels may be important. Soils with ESP values of 15% or more are considered sodic. These levels of sodium cause clay particles to disperse in the soil because of the nature of the sodium ion. The dispersed clay particles cause low soil permeability, poor soil aeration, and difficulty in seedling emergence in fine-textured soils.

Sodic soil conditions may be corrected by adding soluble calcium to the soil to displace some of the sodium on the exchange sites and by removing the displaced sodium through leaching. Management of sodium-affected soils is discussed in Chapter 7.

Geology

Geologic formations and discontinuities that might cause unexpected flow patterns of applied wastewater to the groundwater should be identified in the planning stages of a wastewater irrigation system. If the underlying rock is fractured or crevassed, like limestone, percolating wastewater may reach groundwater before receiving adequate treatment. If there is adequate soil depth for retention of wastewater constituents, there is less concern for geologic discontinuities. Information on geologic discontinuities can be obtained from the USGS.

Groundwater

Depth to groundwater and groundwater quality are two important aspects of site evaluation. Shallow groundwater can interfere with crop growth and the long-term percolation of treated water. Generally a depth to groundwater of 3 to 4 ft (0.9 to 1.2 m) or more is preferred. Lesser depths will require subsurface drainage (see Chapter 8) unless the shallow groundwater occurs only in the winter and no permanent crops susceptible to poor drainage are grown. If storage or stream discharge of wastewater is practiced in the winter, a seasonally high water table may be acceptable.

Information on groundwater quality and use is generally available from the California Department of Water Resources or from the Regional Water Quality Control Board basin plans. The basin plans also have quality objectives for different groundwater aquifers. The expected quality of the percolate must not cause the groundwater to fall below these quality objectives. Because it is difficult and expensive to predict the dilution of percolate by groundwater, the conservative approach is to set the percolate quality equal to the groundwater objective.

Land Use

The existing and proposed land uses and the zoning of the potential site and adjacent lands are important to site selection. The proposed effluent irrigation system should conform to local land-use goals and objectives.

Wastewater irrigation systems can conform with the following land-use objectives:

1. Protection of open space that is used for wastewater irrigation
2. Production of agricultural or forest products using renovated water on the wastewater irrigation site
3. Reclamation of land by using renovated water to establish vegetation on scarred land or saline-alkaline soils
4. Augmentation of parklands by irrigating such lands with renovated water

5. Management of flood plains by using flood-plain areas for wastewater irrigation, thus precluding land development on such sites
6. Formation of buffer areas around major public facilities, such as airports.

To evaluate present and planned land uses, city, county, and regional land-use plans should be consulted. Because such plans often do not reflect actual current land use, site visits are recommended to determine existing land use. Aerial photographic maps may be obtained from the SCS or from the local assessor's office and should also be updated during site visits. Other useful information may be available from the USGS and the Environmental Protection Agency, including true-color, false-color infrared, and color infrared aerial photos of the study area.

Climate

An evaluation of climatic factors such as precipitation, evapotranspiration, temperature, and wind is used in determining (1) the crop water balance, (2) the length of the growing season, (3) the number of days when the system cannot be operated, (4) the storage capacity requirement, and (5) the amount of stormwater runoff to be expected. Information on evapotranspiration and crop water use in California is presented in Chapter 5.

Sufficient climatic data are generally available for most locations from three publications of the National Oceanic and Atmospheric Administration (NOAA--formerly the U.S. Weather Bureau). The local office of NOAA or the National Climatic Center of NOAA in Asheville, North Carolina, 28801, can be contacted for these publications.

The Monthly Summary of Climatic Data provides basic data, such as total precipitation, maximum and minimum temperatures, and relative humidity, for each day of the month for every weather station in a given area. Evaporation data are also given where available.

The Climatic Summary of the United States provides 10-year summaries of data for the same stations in the same given areas. This form of the data is convenient for use in most of the evaluations that must be made and includes:

1. Total precipitation for each month of the 10-year period
2. Total snowfall for each month of the period
3. Mean number of days with precipitation exceeding 0.10 and 0.50 inch (0.25 and 1.3 cm) for each month
4. Mean temperature for each month for the period
5. Mean daily maximum and minimum temperatures for each month
6. Mean number of days per month with temperatures less than or equal to 32°F (0°C) and greater than or equal to 90°F (32.5°C).

Local Climatological Data, an annual summary with comparative data, is published for a relatively small number of major weather stations. Among the most useful data contained in the publication are the normals, means, and extremes, which are based on all data for that station on record to date. To use such data, correlation may be required with a station reasonably close to the site.

FIELD INVESTIGATIONS

Field investigations that may be incorporated into the site characterization include site inspections, soil-profile evaluations, and infiltration-rate testing.

Site Inspection

Site inspections are necessary to assess the existing land use, drainage features, and topography. In addition, site inspections are important in allowing observation of existing vegetation and current or past irrigation practices. The species of natural vegetation that may be growing in an unirrigated area can be used as an indication of those soil characteristics that affect plant growth. They should not be used as the only means of problem assessment; however, if their occurrence is noted, detailed soil investigations should be conducted to assess the extent of the problem. Some plant species and their probable indication of soil characteristics are given in Table 4-2.

If the site has been farmed and irrigated, it is very helpful to interview the farmer or irrigator. It is important to know past practices in cropping, irrigation rates, drying times needed between irrigations, and use of fertilizers or soil amendments. The locations

Table 4-2. Probable soil characteristics indicated by plants in the western states [5].

Plant species	Probable indication
Alpine fir	Poorly drained soil, high water table
Spruce	Poorly drained soil, high water table
Cattails	Poorly drained soil, high water table
Sedges	Poorly drained soil, high water table
Willow	Poorly drained soil, high water table
Dogwood	Poorly drained soil, high water table
Needle and thread grass	Light textured soil
Western wheat grass	Heavy textured, poorly drained soil
Salt grass	Highly saline soil
Mexican fireweed	Highly saline soil
Grease wood	Highly saline soil, sodium problems
Foxtail	Salt, sodium, high water table
Ponderosa pine	Dry soil
Sagebrush	Deep soil

and specific uses of wells on the site and surrounding parcels should be determined. If the farmer is not available, the farm adviser, local SCS representatives, or other farmers in the area should be contacted.

Soil Profile Evaluation

Following the initial site inspection, some subsurface exploration may be necessary. If a detailed soil survey exists, the field work may involve only spot verification of the survey using a hand-held soil auger. If the survey is more general, or if specific concerns exist about subsurface features, backhoe pits may be required. Backhoe pits are recommended over soil borings because they (1) allow direct viewing of the soil profile, (2) can obtain accurate samples (if needed), (3) allow a wide view of any conditions such as fractured, near-surface rock, hardpan or clay layers that may exist, and (4) can reveal mottling or bluish/grayish color streaks (indicates high groundwater has occurred). The depth of the evaluation can range from 4 to 6 ft (1.2 to 1.8 m).

Infiltration Rate Testing

There are many potential techniques for measuring infiltration including flooding basin, cylinder infiltrometers, sprinkler infiltrometers and air-entry permeameters. A comparison of these four techniques is presented in Table 4-3. For irrigation systems, the cylinder infiltrometer test is used widely and is described in the following paragraphs. The other tests are described adequately elsewhere [1,4,6].

To conduct the cylinder infiltrometer test, a metal cylinder is driven carefully into the soil to a depth of about 6 inches (15 cm). Ideally, the measurement cylinder should be 18 inches (45 cm) or larger in diameter and 12 to 18 inches (30 to 45 cm) in length. To minimize divergent flow (laterally), a buffer zone is provided by diking the area around the cylinder with a 6-inch (15-cm) earthen berm or by driving in another cylinder of larger diameter. Care must be taken to maintain water levels in the inner and outer cylinders at about the same level during the measurements.

Table 4-3. Comparison of infiltration measurement techniques [1].

Measurement technique	Water used per test (gal)	Time per test (hour)	Equipment needed	Comments
Flooding basin	500-2,000	4-12	Backhoe or blade	Tensiometers may be used.
Cylinder infiltrometer	100-185	1-6	Cylinder or earthen berm	Should use large-diameter cyclinders.
Sprinkler infiltrometer	265-320	1.5-3	Pump, pressure, tank, sprinkler, cans	For sprinkler applications, soil should be at field capacity before test.
Air entry permeameter (AEP)	2.6	0.5-1	AEP apparatus, standpipe with reservoir	Measures vertical hydraulic conductivity. If used to measure rates of several soil layers, rate is harmonic mean of conductivities from all soil layers.

Installation of the cylinder should disturb the soil as little as possible. This generally requires thin-walled cylinders with a beveled edge and very careful driving techniques. In soft soils, cylinders may be pushed or jacked in. In harder soils, they must be driven in. The cylinders must be kept straight during this process, especially avoiding a rocking or tilting motion to advance them downward. In cohesionless coarse sands and gravels, a poor bond between the soil and the metal cylinder often results, allowing seepage around the edge of the cylinder. Thus, tamping of the soil around the inside perimeter of the ring is recommended.

If the cylinder is installed properly and the test carefully performed, the technique should produce data that at least approximates the vertical component of flow. In most soils, as the wetting front advances downward through the profile, the infiltration rate will decrease with time and approach a steady-state value asymptotically. This may require as little as 20 to 30 min in some soils and many hours in others. Certainly, one cannot terminate a test until the steady-state condition is attained or the results will be totally meaningless. Because the steady-state infiltration rate is an approximate measurement of the saturated vertical permeability of the soil horizon at which the infiltration test is conducted, the permeability of sub-surface horizons may be estimated by excavating a wide pit to the depth of the horizon in question and conducting an infiltrometer test as described above.

It is common to have wide variations in measurements of infiltration rate over a potential irrigation site. The minimum number of tests depends on the number and variability of the soil types encountered. A total of 5 tests may be adequate for a small parcel (5 to 10 acres), whereas 10 to 12 tests may be needed for a 40-acre site. When all the data are reduced, the average infiltration rate should be calculated, and any value greater than two standard deviations above the average should be excluded. The average should be recalculated without the high values. Experience has shown that cylinder infiltrometers overestimate the actual infiltration rate. It is recommended that the average of the measured values be divided by 1.4 to obtain the representative rate.

EFFECT OF VEGETATION ON INFILTRATION RATE AND PERMEABILITY

In general, plants tend to increase both the infiltration rate of the soil surface and the permeability of the soil in the root zone. The magnitude of this effect varies among crops. Thus, the crop selected can affect the design application rate of sprinkler distribution systems, which is based on the minimum infiltration rate of the soil surface. Minimum infiltration rate is equivalent to the permeability of the surface soil. Design sprinkler application rates can be increased by 50% over the minimum infiltration rate for most full-cover crops and by 100% for mature (>4 years old), well-managed permanent pastures (see Figure 4-2 and Chapter 8).

Forest surface soils are generally characterized by high infiltration rates owing to the presence of high levels of organic matter. The infiltration rates observed in most forest surface soils exceed all but the most extreme rainfall intensities. Therefore, surface infiltration rate is not usually a limiting factor in establishing the design application rate for sprinkler distribution in forest systems.

In addition, the permeability of subsurface forest soil horizons is generally improved over that found under other vegetation systems because there is (1) no tillage, (2) minimum compaction from vehicular traffic, (3) decomposition of deep penetrating roots, and (4) a well-developed structure as a result of the increased organic matter content and microbial activity. Where subfreezing temperatures are encountered, the forest floor serves to insulate the soil so that soil freezing, if it does occur, occurs slowly and does not penetrate deeply. Consequently, wastewater application can often continue through the winter in forest systems.

MAINTENANCE OF INFILTRATION RATES

Soil infiltration rates can be reduced by compaction or by surface sealing. The causes include (1) compaction of the surface from machine working, (2) compaction from grazing animals when the soil is wet, (3) a clay crust caused by water droplets or water flowing over the surface (fine particles are fitted around larger particles to form a relatively impervious seal), or (4) clogging due

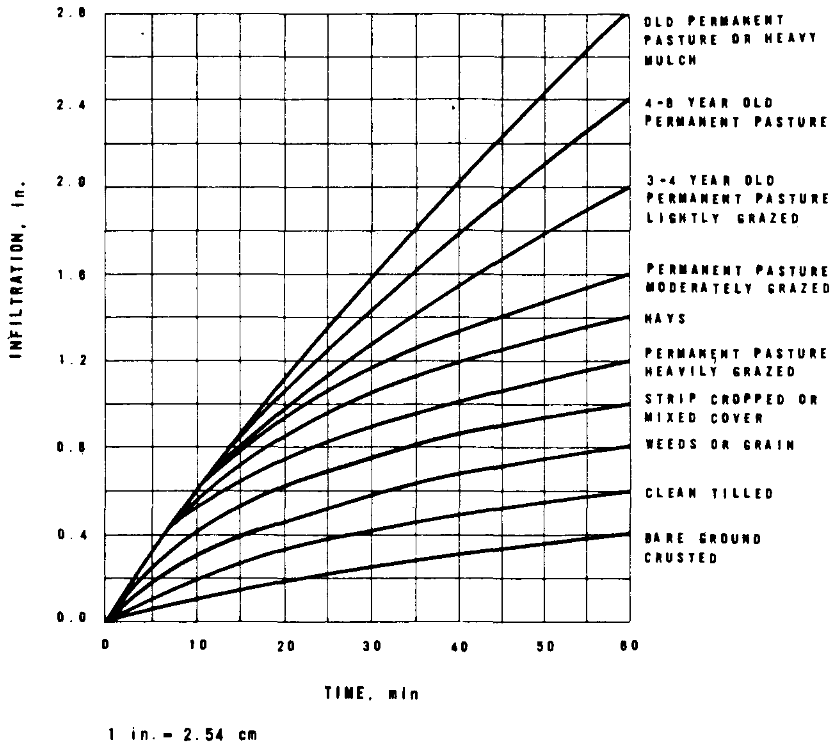


Figure 4-2. Infiltration rates for various crops [7].

to suspended particles, buildup of organic matter, or trapped gases. This latter cause is not usually encountered where wastewater is applied at a rate to meet the crop needs.

The compaction or surface layer can be broken up by plowing, cultivation, or any other tilling of the soil that will result in increased water intake. Tillage beyond the point of breaking up an impermeable layer is generally harmful in that it results in further soil compaction. The effect of surface sealing on infiltration can be greatly reduced, and possibly eliminated, by growing grass or another close-growing crop. Maintenance of soil organic matter by using high-residue crops, such as barley, and plowing under stubble is another step that helps maintain soil infiltration rates.

For pasture that is grazed, it is important to keep the grazing animals off the pasture until it is sufficiently dry. This reduces the compaction that can be harmful, especially to fine-textured soils.

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CHAPTER 5

CROP WATER USE

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INTRODUCTION

Two of the important parameters needing evaluation in development of irrigation and storage facilities for reclaimed water irrigation systems are losses through the process of evaporation and gains from precipitation. In fact this chapter could appropriately be titled "Net Losses in Surface-Atmosphere Interactions." In this chapter procedures are developed for estimating expected losses of water through transpiration (T) by plants and evaporation (E) from plant, soil, or pond surfaces. The combined loss for a cropped surface is commonly referred to as evapotranspiration (ET). Extensive precipitation records are already available.

In the past, well-watered, short green crops fully shading the ground have been used to evaluate the impact of climate on evapotranspiration. The term potential evapotranspiration (PET) was suggested by early researchers (Thornthwaite [1] and Penman [2]). More recently Doorenbos and Pruitt [3], expanding the Penman definition, described a "reference crop evapotranspiration", ET_o, as the "rate of evapotranspiration from an extended surface of 8 to 15 cm (3-6 inch) tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water." A term more commonly used is simply "reference evapotranspiration" with the crop specified. This term, with grass as the reference crop, was selected several years ago by an Interagency Group for use in California and was used by Pruitt et al. [4].

Values of ET_o are considered herein to provide direct estimates of water loss for a well-managed pasture. For other crops ET is estimated by multiplying ET_o values by recommended crop coefficients (k_c).

An analysis of storage needs for reclaimed water projects requires consideration not of ET alone, but of the annual (and monthly) excess of ET over P. The use of only normal or average values is not adequate due to the natural variation of both; hence long-term records of ET and P are required. Also, because the two are not independent[1/], a frequency distribution of (ET - P) cannot be developed by separate assessments of records of ET and of P; rather (ET - P) data for a number of years must be available or generated.

Since the records of measured ET_o are limited to a few locations in California, the required long-term data for ET_o - P must be generated from year-by-year or even month-by-month estimates of ET_o. This could be accomplished using weather data and appropriate prediction equations, were it not for the paucity of required climatic data for equations that are sensitive enough to fully respond to temporal variations of ET_o.

Fortunately there are many locations in California with long term records of monthly pan evaporation (E_p). Except for 30 or so locations where pans were sited in an irrigated turfgrass environment, or in areas with continuously dry surroundings, selection of appropriate pan coefficients for estimating ET_o has been considered difficult[2/]. However, a procedure proposed herein should allow use of most of the evaporation pan records available in California to develop long-term estimates of ET_o.

In design of the irrigation system to handle the requirements of crops during midsummer, monthly values of ET (or ET - P for areas with summer rainfall) do not offer the necessary detail for developing peak demand information. This is especially true for shallow or sandy soils or shallow-rooted crops. Essentially, daily records of estimated ET for the months of June or July over a several-year period are needed to determine expected peak demand. Pan evaporation data on a

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1/ The cloudiness needed to produce precipitation reduces ET to lower than normal levels while ET is greatest during clear weather. A regression analysis of a 16-year record for Mar.-Apr. periods at Davis of measured ET for grass versus precipitation, P indicated ET = -0.469 P + 9.22 inches with a correlation coefficient r = 0.90. Annual data suggested ET = -0.231 P + 55.50 inches with r = 0.71.

2/ Several studies have shown the hazard of using pan evaporation data to estimate PET or ET_o without due regard to local pan environment (Ramdas [5], Pruitt [6], DWR [7], and Pruitt and Doorenbos [8], [9]).

daily basis are available from some local records; however, an approach adapted from Jensen and Criddle [10] and Doorenbos and Pruitt [3] is suggested. The design criteria are based upon published information on extreme maximum values of pan evaporation at a number of selected weather stations in California and adjacent states [11].

DEVELOPMENT OF REQUIRED BACKGROUND DATA

In this section we will present several methods for determining normal-year ET_0, discuss the availability and application of crop coeffcients to obtain ET(crop), and provide a reference source for obtaining necessary long-term precipitation records for California. These data are required for the ultimate development of long-term records (preferably twenty years or more) of net water loss (ET - P), and for use in subsequent frequency distribution analyses.

Reference Evapotranspiration, ET_0

Three alternative approaches are provided in this chapter for selecting normal-year values of ET_0 for annual, seasonal, or monthly periods for any location in California. These ET_0 values become the basis of development of expected losses, e.g., from pasture and other crops, fallow surfaces, and storage ponds. The approaches are as follows:

1. Bulletin 113-3, published by the California State Department of Water Resources (DWR [7]), provides tables of potential evapotranspiration (PET) for some ten regions of the state, each considered as a zone of similar evaporative demand. An equivalence of ET_0 and PET can be assumed since most of the values of PET they report were based on actual ET by perennial ryegrass or tall fescue. Table 5-1 is a reproduction of their Table 6. Figure 5-9 (page 5-33, following the text) was also reproduced from Bulletin 113-3 [7]. It delineates so-called zones of similar evaporative demand. Data in Table 5-1 can be used for development of monthly, seasonal, or annual totals of ET_0, especially for locations well away (geographically) from the borders separating zones.

Table 5-1. Summary of estimated potential evapotranspiration in California in inches.[a,b] After California DWR Bull. 113-3, [7].

	Northeastern Mountain Valleys	North Coast-Coastal Valleys and Plains	North Coast-Interior Valleys	Sacramento Valley	San Joaquin Valley	Central Coast-Coastal Valleys and Plains	Central Coast-Interior Valleys	South Coast-Coastal Valleys and Plains c	South Coast-Coastal Interior Valleys c	Southern California Desert d
Jan	0.6	0.5	0.8	1.1	0.9	1.8	1.6	1.8	1.7	2.7
Feb	1.0	1.0	1.2	1.8	1.7	2.1	2.1	2.4	2.4	3.6
Mar	2.1	2.0	2.4	3.0	3.2	3.1	3.3	3.1	3.3	5.9
Apr	3.7	2.5	3.4	4.4	4.5	3.9	4.3	3.8	4.2	7.6
May	5.0	3.3	5.0	5.8	6.5	4.7	5.7	4.5	5.1	10.1
Jun	5.8	3.6	5.9	7.3	7.5	4.9	6.2	5.1	6.0	11.4
Jul	7.9	3.5	7.1	7.9	7.8	5.3	6.7	5.5	6.9	11.6
Aug	7.0	3.4	6.2	6.7	6.6	4.8	6.0	5.5	6.7	9.6
Sep	4.9	2.8	4.6	5.2	4.8	3.8	4.8	4.5	5.2	8.5
Oct	2.8	1.7	2.7	3.4	3.3	3.2	3.8	3.4	3.8	6.3
Nov	0.9	1.1	1.2	1.6	1.5	2.2	2.3	2.6	2.3	3.5
Dec	0.5	0.7	0.7	1.0	0.7	1.5	1.5	2.2	1.8	2.0
M-O[e]	39.2	22.8	37.3	43.7	44.3	33.7	40.8	35.4	41.2	71.0
J-D[f]	42.2	26.1	41.2	49.2	49.0	41.3	48.3	44.4	49.4	82.8

a. Potential evapotranspiration (PET) = ET of grass = reference evapotranspiration, ET_o.

b. Calculated from area average pan evaporation (E_p) data and recommended statewide average monthly k_p values [7] except as noted.

c. No evaporation data (irrigated pasture environment) available. PET estimates based upon estimated evaporation.

d. An estimate of ET – grass for Imperial Valley. Calculated by first author from ET by alfalfa (excluding two weeks following cutting) as observed by Robert D. LeMert, USDA-ARS, Brawley. (A 10-15% lower ET by grass than by alfalfa was assumed.)

e. March through October (principal growing season).

f. January through December.

2. For other areas, estimates of ET_0 (on an annual basis only) can be obtained for any location in California by multiplying a pan coefficient (K_p) of 0.80 by a value of annual evaporative demand E_0 as obtained by interpolation from Plate No. 1 in DWR Bulletin 113-3 [7]. The term E_0 as presented herein, represents the evaporation expected from a National Weather Service Class "A" pan located in an irrigated pasture (or comparable environment). (See Figure 5-10 on page 5-34 for a reduced copy of this plate.)
3. A third alternative is believed to offer improved overall accuracy for much of the state. The isoline maps in a University of California bulletin (Pruitt et al. [4]) can be used to obtain annual, seasonal, or monthly estimates of ET_0 for normal-year conditions for any location in California. As illustrated later, estimates for periods shorter than one month can be developed. Copies (reduced in size) of the twelve isoline maps are included in this chapter, one for each month of the year (Fig. 5-11, pages 5-35 through 5-46).

ET or E for Cropped and Noncropped Surfaces

Estimates of annual, seasonal, or monthly losses of water from cropped or noncropped soil or water surfaces can be obtained by applying crop coefficient (k_c) values to ET_0 estimates. ET_0 itself can serve as an estimate of ET losses by a well-managed pasture assuming $k_c = 1.0$. For most crops under full-cover conditions, and for water surfaces or wet bare soil, k_c values greater than 1.0 are appropriate[3/]. For fallow conditions, the soil surface is frequently not wet and for early stages of crop growth, ET is usually quite limited. Hence, k_c values well below 1.0 are common, unless frequent rain or irrigations are involved.

The sources of k_c values for various cropping patterns and for annual, monthly or shorter periods are outlined below:

3/ For a given climatic condition, the ET of many crops exceeds ET_0. Involved are their taller, aerodynamically rougher canopies, a slightly lower reflectance of incoming solar radiation, and a somewhat cooler canopy with lower long-wave radiation losses than for grass.

1. Annual k_c estimates: Table 5-2 provides recommended k_c values on an annual basis to be multiplied by annual ET_o estimates. Such data may be valuable for preliminary feasibility analysis.
2. Alternate sources of, and shorter-period estimates of k_c:
   a) Table 5-12 on page 5-29 at the end of the text provides estimates of monthly k_c data for a number of crops. This table is an adaptation of k_p coefficients published in Table 5 of DWR Bull. 113-3 [7].
   b) Table 5-13 (pp. 5-30 and 5-31) provides a sample of 10- to 11-day recommended k_c values for a number of crops grown in several areas of the state. These data were adopted, from a final report on irrigation management programs by Fereres, et al. [12], and other studies cited in Table 5-13 footnotes. Copies of this report are available from the Dept. of Land, Air and Water Resources, University of California, Davis.
   c) A bulletin in preparation by Fereres et al. [13], includes more extensive crop coefficient data.

Precipitation

Long-term records of precipitation are available for hundreds of sites in California. An extensive and up-to-date record was published in a DWR Bulletin, "California Rainfall Summary, Monthly Total Precipitation, 1949-1980" [14]. Other sources may be more convenient since the records of the cited reference are contained within micro-fiche frames.

NET WATER USE FOR CROPS WITH YEAR-LONG FULL COVER

In this section, procedures are described and examples given as follows: 1) development of estimates of yearly totals of net water loss for cases involving ET_o, ET(trees) and E(ponds), along with a frequency analysis; 2) same but for separate analyses of wet-season, dry season, and transition months; 3) a comparison of yearly totals based on 1) and 2) above; and 4) development of monthly net water-loss data at a particular probability level, with adjustment to provide agreement with yearly totals under 1) above.

Table 5-2. Recommended crop coefficient (k_c) values to be multiplied by ET_o for estimating ET and E losses for a range of air mass conditions ranging from humid to dry to dry and windy. Included are various perennial crops and evergreen shrubs and trees (nondeciduous) all providing green cover with nearly full shading of the ground surface.[a]

Description	k_c[b] Dry & Humid-Dry-Windy
Water surfaces (shallow ponds, storage reservoirs, etc)[c]	1.05-1.10-1.15
Dark bare soil (constantly moist on surface)	1.05-1.10-1.15
Lighter colored bare soil (constantly moist surface)	1.00-1.05-1.10
Grass pasture (well maintained with rotational grazing)[c]	0.80-0.90-1.00
Grass-clover (or alfalfa) pasture with >60% ground cover left after grazing[b]	1.00-1.05-1.10
Alfalfa (grown for hay with cuttings every 30-35 days)[c]	0.85-0.95-1.05
Shrubbery (various evergreen species – low stomatal control)[d]	1.05-1.15-1.20
Evergreen trees (various species – high soil moisture – low stomatal control)[e]	1.10-1.20-1.30

a. For mountainous regions and in northern California, pastures and alfalfa may go dormant in winter resulting in lowered k_c values.

b. Some regions of the state experience a range of conditions during the year making it difficult to select a single k_c for use in an analysis involving annual totals of ET. Since a large portion of the total annual ET takes place in Apr.-Sep., the column selected to represent general climate conditions should be based on conditions prevailing during Apr.-Sep.

c. Based on k_c values suggested by Doorenbos and Pruitt, [3].

d. Based on assumptions that some species of evergreen shrubs offer very little stomatal control when grown in constantly moist soil and that reflection and roughness characteristics would result in k_c values similar to those of a number of agricultural row crops when they are fully shading the ground, e.g., tomatoes, sugarbeets, corn, etc. [3, 15].

e. Assuming some species of evergreen trees need k_c values similar to those suggested for mature apple, cherry, and walnut orchards when grown with a cover crop (Middleton et al. [16], and Doorenbos and Pruitt [3]). Many studies on salt cedar (Tamarix chinensis Lour) lead the authors to believe that these coefficients are conservative if anything. For example see Davenport et al. [17, 18], Gay and Sammis [19], and Van Hylckama [20].

Yearly Totals Based on Annual Data

Preliminary evaluations for storage requirements of slow-rate reclaimed water systems can be based on estimates of yearly totals of evapotranspiration (ET) and/or of open water evaporation (E) from ponds, along with measured precipitation (P).

The EPA Process Design Manual [21] provides a map on page 2-11 with isolines of annual potential evapotranspiration minus precipitation (PET - P) for the entire contiguous USA. This map reproduced from Flach [22], although a valuable contribution, is not recommended for use in California for two reasons: (1) data developed within the state are likely to be more reliable; and (2) data for estimated or measured ET minus precipitation are needed for a number of years of record in order to develop design information related to a selected frequency of occurrence.

The simplest design procedure is for those systems which will involve the growing of some perennial crop which maintains year-round, full cover of green growth, e.g., pasture and evergreen shrubs or trees. As indicated earlier, reference evapotranspiration (ET_o) will be used herein as a foundation for calculating losses for various cropped or water storage areas with ET_o itself serving as an estimate for a well-managed pasture.

For system design based on annual data the following steps are recommended:

1. Develop an estimate of normal-year total annual ET_o for the geographical location of interest as described in an earlier section.
2. Using DWR Bulletin 73-79 [23], extract and tabulate annual pan evaporation data (E_p) for a location nearest the site of interest but with a record of 15 years or more of data. Do not combine the records of two or more types of pans for any given site since evaporation is very much a function of type of pan. If possible also avoid use of records involving a change of weather station siting. See U.S. Department of Commerce Bulletin [24].
3. After calculating a mean value of annual E_p divide this value into the estimated annual normal ET_o of (1) above to obtain an average pan coefficient, K_p.

4. Multiply the average K_p by each E_p value tabulated under (2) above to obtain an estimate of ET_o for each year for which pan data are available. If crops or surfaces other than pasture are involved, multiply the ET_o value by appropriate k_c values as given in Table 5-2; e.g., to obtain estimates of evaporation from storage ponds, E(pond) or evapotranspiration from trees, ET(trees).
5. Using California's DWR Bulletin "California Rainfall Summary" [14], extract from microfiche frames, a record of the total annual rainfall for the same years of record as for the available E_p data tabulated under (2) above.
6. Subtract precipitation values from respective tabulated ET or E data under (4) above.
7. Run a frequency distribution analysis of estimated losses minus precipitation.

Data for 19 years from Davis, California are used in Example 5-1 to illustrate the steps outlined above with Steps 2-6 developed in Table 5-3a. Table 5-3b in Example 5-1 illustrates the development of the frequency distribution data. Figure 5-1, based on an assumed normal distribution, provides a plot of the results of the analysis developed in Example 5-1. The result of a separate frequency analysis of ET - P for a 16-year record of lysimeter measurements of ET for grass is also presented for comparison with the ET_o - P data. These measured data appear to validate the approach suggested under Steps 1 through 4, showing close agreement with the derived ET_o - P data except for the two years of highest losses.

The 90% probability level indicated in Fig. 5-1 is shown for illustration only, not necessarily a recommendation. Indicated is a 90% probability that net losses involving ET_o, E(pond), or ET(trees) should equal or exceed 20, 25, or 29 inches respectively (50.8, 63.5 or 73.7 cm), at Davis, California, in any given year. Of significance is the fact that for a reclaimed water system involving little, if any, deep percolation loss, the land acreage requirement for evergreen trees would be only 70% of that for a system involving grass pasture.

Example 5-1. E - P and ET - P for 19 years at Davis. (Yearly totals based on annual data)

Step 1. Normal-year ET_o (three alternative methods illustrated)

a)	ET_o = 49.2 inch	Table 5-1 (Sacramento Valley)
or b)	ET_o = 0.80 x 65 = 52.0 inch	Annual E map in Figure 5-10
or c)	ET_o = 51.78 inch	12-month summary, Isoline maps in Figure 5-11.

$$\text{in/mo} = \frac{\text{days in mo. x mm/day}}{25.4}$$

Step 2. Annual E_p (Oct.-Sep.) from DWR Bull. 73-79 [23] pg. 28. Class A pan in an "A" environment. Missing data for years 1963, 1964, and 1975 obtained from local records to achieve a 19-year record. Note: A record from any one of the other Davis pans could have been used.

Step 3. Divide normal-year ET_o (from Step 1) by E_p giving K_p = 51.78/70.79 = 0.731.

Step 4. Multiply each year's E_p by K_p to estimate ET_o. Multiply k_c values from Table 5-2 by ET_o to estimate ET(trees) and E(pond).

Step 5. Record precipitation, P obtained from DWR Bull. "California rainfall summary" [14].

Step 6. Subtract Precipitation from ET and E totals.

Table 5-3a. Illustration for Davis, Ca. of Steps 2-6 using annual data.

Year	E_p(Oct-Sep) mm a/	E_p(Oct-Sep) Inch	ET_o Inch b/	ET(trees) Inch b/	E(pond) Inch b/	P Inch c/	ET_o-P Inch d/	ET(trees) - P Inch d/	E(pond) - P Inch d/
59-60	2029	79.9	58.4	70.1	64.2	10.7	47.4	59.4	53.5
60-61	1775	69.9	51.1	63.1	56.2	12.8	38.3	48.5	43.4
61-62	1712	67.4	49.3	59.2	54.2	15.0	34.3	44.2	39.2
62-63	1520	59.8	43.7	52.4	48.1	27.2	16.5	25.2	20.9
63-64	1786	70.3	51.4	61.7	56.5	11.1	40.3	50.6	45.4
64-65	1634	64.3	47.0	56.4	51.7	19.0	28.0	37.4	32.7
65-66	1732	68.2	49.9	59.9	54.9	11.1	38.8	48.8	43.8
66-67	1544	60.8	44.4	53.2	48.8	27.4	17.0	25.8	21.4
67-68	1867	73.5	53.7	64.4	59.1	11.6	42.1	52.8	47.5
68-69	1711	67.4	49.2	59.0	54.1	24.5	24.7	34.5	29.6
69-70	1872	73.7	53.9	64.7	59.3	17.0	36.9	47.7	42.3
70-71	1738	68.4	50.0	60.0	55.0	16.4	33.6	43.6	38.6
71-72	1820	71.7	52.4	62.9	57.6	9.4	43.0	53.5	48.2
72-73	1791	70.5	51.5	61.8	56.7	27.0	24.5	34.8	29.7
73-74	1848	72.8	53.2	63.8	58.5	21.4	31.8	42.4	37.1
74-75	1821	71.7	52.4	62.9	57.6	16.9	35.5	46.0	40.7
75-76	2036	80.2	58.6	70.3	64.5	6.8	51.8	63.5	57.7
76-77	1980	78.0	57.0	68.4	62.7	7.6	49.4	60.8	55.1
77-78	1945	76.6	56.0	67.2	61.6	27.0	29.0	40.2	34.6
Sum		1345.1	983.1	1179.6	1081.0	319.9	663.2	859.7	761.4
Average		70.79		62.1	56.9	16.84	34.91	45.3	40.1

a/ Step 2.
b/ Steps 3 and 4.
c/ Step 5. Note: Some discrepancies with DWR [14] may be noted since local records were used in this example.
d/ Step 6.

Step 7. Illustration of Frequency Distribution Analysis.

a) Calculate probability level from 100 m/(n + 1) where m = ranking and n = years of record.

b) For systems involved, list data for water loss - P from Table 5-3a., ranked in order of descending magnitude.

c) Plot data on normal probability paper as in Figure 5-1.

Table 5-3b. Ranking of estimated annual totals of water loss - P.

m	$\frac{100m}{19 + 1}$	ET_o - P Inch	ET(trees) - P Inch	E (pond) - P Inch
1	5	51.8	63.5	57.7
2	10	49.4	60.8	55.1
3	15	47.7	59.4	53.5
4	20	43.0	53.5	48.2
5	25	42.1	52.8	47.5
6	30	40.3	50.6	45.4
7	35	38.8	48.8	43.8
8	40	38.3	48.5	43.4
9	45	36.9	47.7	42.3
10	50	35.5	46.0	40.7
11	55	34.3	44.2	39.2
12	60	33.6	43.6	38.6
13	65	31.8	42.4	37.1
14	70	29.0	40.2	34.6
15	75	28.0	37.4	32.7
16	80	24.7	34.8	29.7
17	85	24.5	34.5	29.6
18	90	17.0	25.8	21.4
19	95	16.5	25.2	20.9

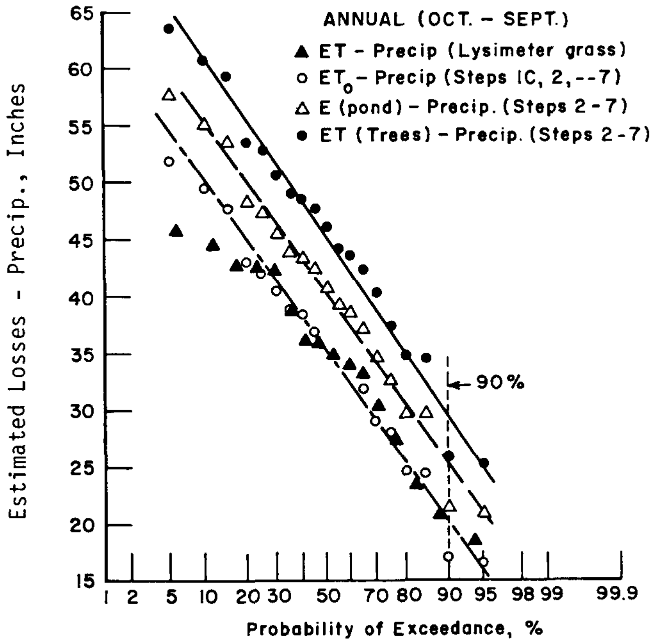

Figure 5-1. Frequency distribution analysis of data from Table 5-3b in Example 5-1 for ET_0, ET(trees), and E(pond), all minus precipitation. Yearly totals for hydrologic years (Oct.-Sept.), Davis, Calif. An analysis of measured ET(grass) - P (not tabulated in Table 5-3b) is shown for comparison with ET_0 - P. Straight lines are from a fitting by eye.

Table 5-14a, b, and c following the text can be used to determine the risk (probability) that an event with a specified probability will occur during one or more, two or more, and three or more years within a selected design period. For example, ET - P has a 10% probability of being less than 20 inches (50.8 cm) in any given year (Figure 5-1). Using Table 5-14a, b, and c, one can calculate that the chances of ET - P being less than 20 inches on one or more, two or more, and three or more years during a 15-year design period, are 0.794, 0.451, and 0.184, respectively.

Seasonal Totals Based on Monthly Data

In many cases an analysis based on yearly totals may be inadequate to meet needs. The following section provides an example, again for a location in the Sacramento Valley (Davis, Ca.), of separate seasonal analyses with the year partitioned into a predominantly wet season (Nov.-Mar.), a predominantly dry season (May-Sept.), and two transition months (Oct. and Apr.). For many areas of California with its predominantly Mediterranean climate, such a grouping of months is recommended. For some areas of the state, however, other groupings may be desirable.

Wet Season

Example 5-2 provides a compilation of data and a frequency analysis for the predominantly wet season at Davis (Nov.-Mar.). Results of the measured ET(grass) are again shown to be in good agreement with the ET_0 calculations using procedures proposed herein. Figure 5-2 indicates that in any given year, there is a 90% probability that the excess of P over ET would be equal to or less than 16 and 14 inches (40.6 and 35.6 cm) for systems involving ET_0 and ET(trees), respectively. It would follow that, for storage ponds in this case, the excess would be around 15 inches (38 cm). Table 5-14 can again be used to determine risk of occurrence of excesses greater than the above for various design periods.

In areas where precipitation can greatly exceed the evaporative demand during the wet season of some years, a designer of wastewater systems would normally apply the water balance data to the storage pond areas only. The excess of P over ET in the cropped land area would merely go to deep percolation and directly into drainage channels. In areas where ET - P remains positive even during wet seasons, or in much wetter regions if deep percolation or run-off are restricted, water balance calculations would be required for both storage pond and cropped areas.

Example 5-2: ET - P for 19 years at Davis (wet-season analysis for November through March).

Step 1. Normal-year ET_o

a) ET_o = 8.5 inch Σ Nov.-Mar. Table 5-1,

b) Annual potential evaporation data not applicable.

or

c) ET_o = 8.68 inch Σ Nov.-Mar. from Isoline maps in Figure 5-11

Table 5-4. Example calculation for Davis, California for estimating November-March ET_o and ET (evergreen trees), and a frequency distribution analysis of expected water losses minus precipitation.

Year	E_p(Nov-Mar) mm a/	E_p(Nov-Mar) Inch	ET_o Inch b/	ET(trees) Inch b/	P Inch c/	ET_o-P Inch d/	ET(trees) - P Inch d/	$\frac{100m}{19+1}$ e/	ET_o-P Inch e/	ET(trees) - P Inch e/
59-60	419	16.4	11.5	13.8	9.3	2.2	4.5	5	8.9	11.2
60-61	305	12.0	8.4	10.1	12.0	-3.6	-1.9	10	4.6	6.7
61-62	318	12.5	8.7	10.4	14.8	-6.1	-4.4	15	2.8	4.8
62-63	265	10.4	7.3	8.8	14.5	-7.2	-5.7	20	2.2	4.5
63-64	366	14.4	10.1	12.1	9.1	1.0	3.0	25	1.0	3.0
64-65	278	10.9	7.6	9.1	13.9	-6.3	-4.8	30	-2.2	-0.6
65-66	286	11.2	7.8	9.4	10.0	-2.2	-0.6	35	-2.4	-0.7
66-67	249	9.8	6.9	8.3	22.5	-15.6	-14.2	40	-3.6	-1.9
67-68	295	11.9	8.3	10.0	10.7	-2.4	-0.7	45	-5.5	-3.8
68-69	274	11.2	7.8	9.4	22.3	-14.5	-12.9	50	-5.8	-3.9
69-70	356	14.0	9.8	11.8	15.6	5.8	-3.8	55	-6.1	-4.4
70-71	309	11.7	8.2	9.8	13.7	-5.5	-3.9	60	-6.3	-4.8
71-72	359	14.1	9.9	11.9	7.1	2.8	4.8	65	-7.0	-5.4
72-73	266	10.5	7.4	8.9	24.1	-16.7	-15.2	70	-7.2	-5.7
73-74	276	10.9	7.6	9.1	18.1	-10.5	-9.0	75	-10.5	-9.0
74-75	295	11.6	8.1	9.7	15.1	-7.0	-5.4	80	-14.5	-12.9
75-76	418	16.5	11.6	13.9	2.7	8.9	11.2	85	-15.6	-14.2
76-77	374	14.7	10.3	12.4	5.7	4.6	6.7	90	-16.2	-14.5
77-78	306	12.0	8.4	10.1	24.6	-16.2	14.5	95	-16.7	-15.2
Average		12.46		10.47	13.99	-5.27	-3.52			

a. Step 2 – From Bull. 73-79 [23], pp. 28. Class A pan in an "A" environment. Σ of Nov-Mar evaporation with missing data for years 1964 and 1975 obtained from local records.

b. Steps 3-4 – Using mean Kp = 8.68/12.46 = 0.70 for ET_o estimates and a k_c of 1.20 from Table 5-2 for evergreen trees (8.68" from Step 1c).

c. Step 5 – Precipitation data summed for Nov.-Mar. from microfiche frames of DWR Bull. California rainfall summary [14].

d. Step 6 – Subtract precipitation from ET_o and ET(trees).

e. Step 7 – Distribution analysis.

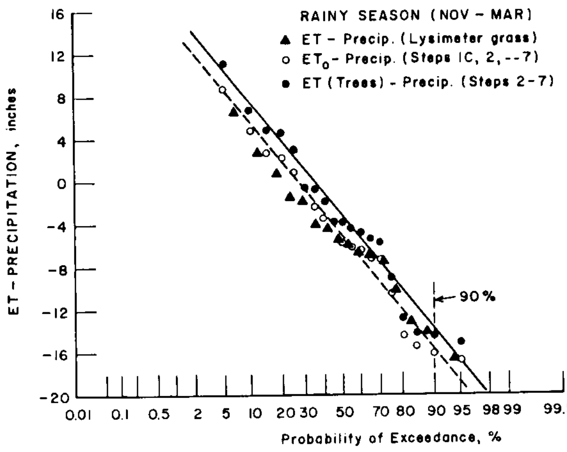

Figure 5-2. Frequency distribution analysis for ET_o - P and ET(trees) - P. An analysis of measured ET(grass) - P is shown for comparison. Davis, California. Rainy Season (November through March).

Dry Season and Transition Months

Specific examples of additional analyses are not laid out in detail although Tables 5-5 and 5-6 provide the necessary calculations for a dry season period (May through September) and for a combination of transition months (i.e., April and October).

Figure 5-3 presents the results of frequency distribution analyses for both sets of data. In any given year, there is a 90% probability that net losses by ET_0 and ET(trees) for the dry season would be equal to or greater than 31 or 37 inches (78.7 or 93.9 cm), respectively. For the two transition months (April and October), corresponding values would be 4 and 5 inches (10.2 and 12.7 cm), respectively. It is obvious from the results of these two months, however, that there is a marked departure from a normal distribution for the wettest year (1962-63). Not only did this hydrologic year have the lowest ET_0 for October and April, but the rain totaled some 11.87 inches. There have been, in a 110-year record, only two other years when P totaled greater than 5.8 inches (14.7 cm). In 1879-80 total P for Oct. and Apr. was 7.8 inches (19.8 cm) and in 1889-90 the total was 9.7 inches (24.6 cm).

The data to the far left in Figure 5-3 are useful for determining the supplemental water supply requirement to maintain good crop or tree growth during high demand years. The analysis suggests that for Davis there is, for example, only a 10% probability that the net demand for irrigation water for May through September would equal or exceed 38 or 46 inches (96.5 or 110.8 cm) for pasture or trees, respectively. The term "net irrigation supply" implies the need for use of an irrigation efficiency value to develop gross requirements (see Chapter 8).

Yearly Totals--Annual Data Versus Composite of Seasonal Data

Earlier a precautionary note was issued against using frequency distribution analyses for separate seasons. A comparison of yearly totals determined using the total annual and seasonal techniques is presented in Table 5-7. The yearly totals based on separate-season analyses are fairly close to those in Example 1 from Figure 5-1. In some climates larger differences might be found, and the trends noted do suggest increasing errors can be expected with consideration of

Table 5-5. Calculations for Davis estimating dry-season (May-Sep.) ET_o and ET (evergreen trees), and a frequency distribution analysis of expected water losses minus precipitation.

Year	E_p(May-Sep) mm[a]	E_p(May-Sep) Inch	ET_o Inch[b]	ET(trees) Inch[b]	P Inch[c]	ET_o-P Inch[d]	ET(trees) - P Inch[d]	$\frac{100m}{19+1}$[e]	Ranked ET_o-P Inch[e]	Ranked ET(trees) - P Inch[e]
59-60	1244	49.0	36.7	44.1	0.54	36.2	43.6	5	40.0	48.1
60-61	1139	44.8	33.6	40.3	0.27	33.3	40.0	10	37.8	45.5
61-62	1070	42.1	31.6	37.9	0.07	31.5	37.8	15	37.1	44.7
62-63	1041	41.0	30.8	36.9	0.87	29.9	36.0	20	36.2	43.6
63-64	1124	44.3	33.2	39.9	0.60	32.6	39.3	25	35.3	42.4
64-65	1113	43.8	32.8	39.4	0.58	32.2	38.8	30	35.3	42.4
65-66	1127	44.4	33.3	40.0	0.52	32.8	39.5	35	35.0	42.1
66-67	1073	42.2	31.6	38.0	1.01	30.6	37.0	40	34.8	41.8
67-68	1212	47.7	35.8	42.9	0.50	35.3	42.4	45	34.1	41.3
68-69	1158	45.6	34.2	41.0	0.19	34.0	40.8	50	34.0	40.8
69-70	1193	47.0	35.3	42.3	0.47	34.8	41.8	55	33.3	40.0
70-71	1141	44.9	33.7	40.4	1.29	32.4	39.1	60	32.8	39.5
71-72	1143	45.0	33.7	40.5	1.41	32.3	39.1	65	32.6	39.3
72-73	1193	47.0	35.2	42.3	0.16	35.0	42.1	70	32.4	39.1
73-74	1289	50.7	38.0	45.6	0.93	37.1	44.7	75	32.3	39.1
74-75	1198	47.2	35.4	42.5	0.12	35.3	42.4	80	32.2	38.8
75-76	1310	51.6	38.7	46.4	0.89	37.8	45.5	85	31.5	37.8
76-77	1217	47.9	35.9	43.1	1.83	34.1	41.3	90	30.6	37.0
77-78	1360	53.5	40.1	48.2	0.05	40.0	48.1	95	29.9	36.0
Ave.	1176	46.30	34.72	41.67	0.65	34.1	41.0			

Step 1 - Normal-year ET_o for May-Sept. = 34.72 inch (from Isoline maps, Figure 5-11)

a. Step 2 - Σ May through Sept. pan evaporation from DWR Bull. 73-79 [23].

b. Steps 3-4 – Using mean K_p = 34.72/46.30 = 0.750 for ET_o estimates and a k_c of 1.20 for evergreen trees.

c. Step 5 – Precipitation data summed for May-Sept. from microfiche frames of DWR Bull. "California rainfall summary" [14].

d. Step 6 - Subtract precipitation from ET_o and ET(trees).

e. Step 7 - Distribution analysis.

Table 5-6. Calculations for Davis of ET_o and ET (evergreen trees) for transition periods (Apr. and Oct.).

Year	E_p(Apr-Oct) mm[a]	E_p(Apr-Oct) Inch	ET_o Inch[b]	ET(trees) Inch[b]	P Inch[c]	ET_o-P Inch[d]	ET(trees) - P Inch[d]	$\frac{100m}{19+1}$[e]	Ranked ET_o-P Inch[e]	Ranked ET(trees) - P Inch[e]
59-60	366	14.4	10.0	12.0	0.90	9.1	11.1	5	10.6	12.7
60-61	331	13.0	9.1	10.9	0.53	8.6	10.4	10	9.4	11.4
61-62	324	12.8	8.9	10.7	0.11	8.8	10.6	15	9.1	11.1
62-63	214	8.4	5.9	7.0	11.87	-6.0	-4.9	20	8.8	10.6
63-64	296	11.7	8.2	9.8	1.45	6.7	8.3	25	8.6	10.4
64-65	243	9.6	6.7	8.0	4.56	2.1	3.4	30	8.2	9.9
65-66	319	12.6	8.8	10.5	0.58	8.2	9.9	35	8.0	9.7
66-67	222	8.7	6.1	7.3	3.93	2.2	3.4	40	7.7	9.5
67-68	360	14.2	9.9	11.9	0.47	9.4	11.4	45	7.4	9.2
68-69	279	11.0	7.7	9.2	1.51	6.2	7.7	50	6.7	8.3
69-70	323	12.7	8.9	10.6	0.93	8.0	9.7	55	6.6	8.3
70-71	288	11.3	7.9	9.5	1.29	6.6	8.2	60	6.4	8.2
71-72	318	12.5	8.7	10.5	0.96	7.7	9.5	65	6.2	7.7
72-73	332	13.1	9.1	11.0	2.69	6.4	8.3	70	5.4	7.0
73-74	283	11.1	7.7	9.3	2.33	5.4	7.0	75	5.4	6.9
74-75	328	12.9	9.9	10.8	1.63	7.4	9.2	80	5.2	6.9
75-76	308	12.1	8.4	10.1	3.20	5.2	6.9	85	2.2	3.4
76-77	389	15.3	10.7	12.8	0.12	10.6	12.7	90	2.1	3.4
77-78	279	11.0	7.7	9.2	2.32	5.4	6.9	95	-6.0	-4.9
Ave.	305	12.02	8.38	10.06	2.18	6.2	7.88			

Step 1 - Normal-year ET_o for Apr. and Oct. = 8.38 inch (from Isoline maps, Figure 5-11)

a. Step 2 - Σ Oct. and April pan evaporation from DWR Bull. 73-79 [23] for Hydrologic year beginning in October.

b. Steps 3-4 – Using mean K_p = 8.38/12.02 = 0.697 for ET_o estimates and a k_c of 1.20 for evergreen trees.

c. Step 5 - Precipitation data summed for Apr. and Oct. from microfiche frames of DWR Bull. "California rainfall summary" [14].

d. Step 6 - Subtract precipitation from ET_o and ET(trees).

e. Step 7 - Frequency distribution analysis.

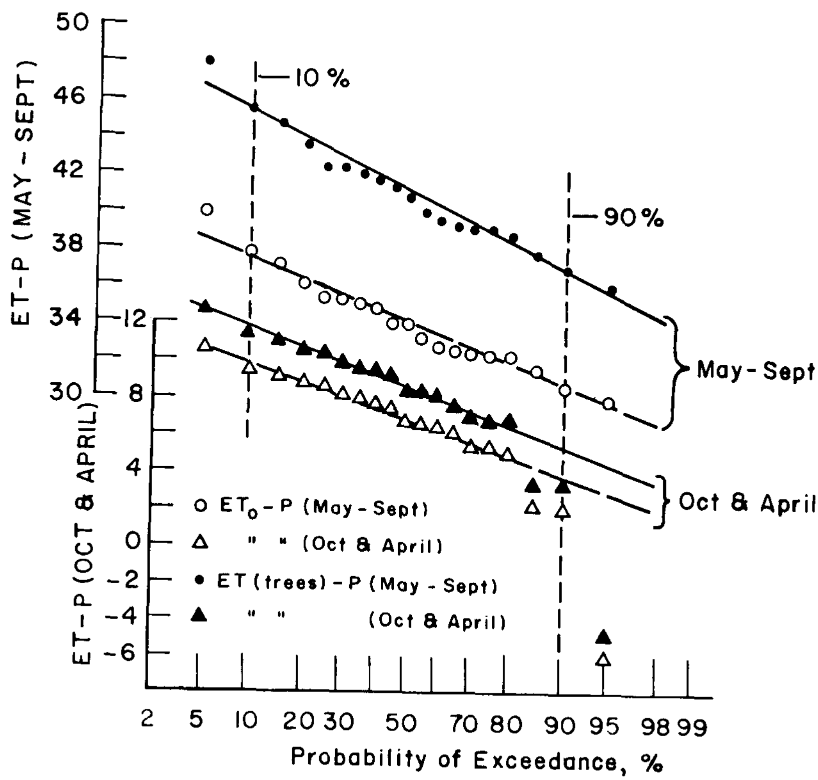

Figure 5-3. Frequency distribution analysis for ET_0 - P and ET(trees) - P for dry season (May-Sept.) and transition months (Oct. and Apr.) at Davis, Calif.

even shorter periods, e.g., monthly. This will be shown later to be the case.

Month-by-Month Net Loss Estimates at a 90% Probability Level

Normally in design of wastewater systems a month-by-month water balance is developed. As indicated earlier, this should not be based on a summation of data from individual month-by-month frequency distribution analyses of expected net losses. Even division of the year into three separate periods as in Tables 5-4, 5-5, and 5-6 resulted in some discrepancy, e.g. in Table 5-7 at the 90% probability of exceedance level, values of annual net losses for ET_0 and ET(trees)

Table 5-7. A comparison of predicted 12-month net water use at the 10% and 90% probability levels as indicated by frequency distribution analysis involving total annual (Example 5-1), and a summation of results from a breakdown into rainy season, dry season, and the transition months of October and April (Figures 5-2 and 5-3).

	Yearly total from annual data (Fig. 5-1)	Rainy-season total (Oct.-Mar.) (Fig. 5-2)	Dry-season total (May-Sept.) (Fig. 5-3)	Transition months total (Apr.-Oct.) (Fig. 5-3)	Yearly total from seasonal analysis	Difference for annual and seasonal analysis
	At 10% probability of exceedance level					
ET_0 - P	50.3	5.5	37.6	9.8	52.9	-2.6
ET (trees) - P	61.0	7.5	45.6	11.8	64.9	-3.9
	At 90% probability of exceedance level					
ET_0 - P	20.3	-15.7	30.8	3.8	18.9	+1.4
ET(trees) - P	29.5	-13.7	37.0	5.4	28.7	+0.8

are 1.4 and 0.8 inches lower, respectively, than for the analyses involving annual totals in Table 3b for the same 19-year period of record. Although these differences are small in the examples for Davis, this might not be true in some locations. Hence, the following example is given to provide a procedure whereby summaries of 12 monthly values of adjusted (ET - P) at a particular probability level (e.g., 90% or 0.9), will result in exactly the same value as that developed under Example 1 using annual totals. Distribution of monthly values for a particular season is based on the distribution of the dominant parameter during that season, i.e., on precipitation for the rainy season months and on ET - P during the other seasons.

Procedures are outlined in Example 5-3 with results tabulated in Table 5-8. Note in Table 5-8 that the sum of monthly values of $(ET_0 - P)_{0.9}$ and $[ET(trees) - P]_{0.9}$ are in agreement with the 20.3 inch (51.56 cm) and 29.5 inch (76.07 cm) at the 90% probability level based on yearly totals using annual data for ET_0 - P and ET(trees) - P, respectively (Table 5-7).

Example 5-3. Development of monthly values of net water loss at a particular probability level, adjusted such that the sum of 12 monthly values will agree with annual totals based on annual data.

Step 1. Listing of monthly normal-year ET_o
Table 5-1 (Sacramento Valley), or from Isoline maps of Figure 5-11 (Davis, Calif.).

Step 2. For crops other than pasture apply k_c values. Table 5-2.

Step 3. List normal monthly precipitation data for nearest location (Davis, Calif.)
Table 3, DWR Bull. "California rainfall summary" [14], (1941-1970 mean).

Step 4. Calculate normal-year ET - P for each month.

Step 5a. For rainy-season: Develop monthly 90% probability values by partitioning a total rainy-season value of adjusted (ET - P) based on the distribution of total P between months.

Adjusted rainy-season $(ET - P)_{0.9}$ total = algebraic sum of $(ET - P)_{0.9}$ for rainy-season and the yearly difference of annual and seasonal analysis: Example with Table 5-7 data.

Adjusted rainy-season $(ET_o - P)_{0.9} = -15.7 + 1.4 = -14.3$

Development of monthly values of adjusted $(ET - P)_{0.9}$ by partition of adjusted rainy-season $(ET - P)_{0.9}$ total, in relation to the distribution of normal precipitation during the rainy-season: Example for month of January.

Adjusted monthly $(ET - P)_{0.9} = -14.3 \times (P_{Jan} \div \Sigma P_{Nov.-Mar.})$

$= -14.3 \times (3.88 \div 13.87) = -4.00''$

Step 5b. For transition and dry-season months develop 90% probability values for each month by application of a correction factor "C" to each month's normal-year value of ET - P, with "C" obtained from dividing the 90% probability value for that season by normal-year Σ (ET - P) for that season.

Example determination of C factor (using data in Table 5-7 and Table 5-8).

C(transition months) = 3.8 (from Table 5-7) ÷ (3.22 + 2.62) = 0.65

C(dry season months) = 30.8 (from Table 5-7) ÷ (5.96 + ... + 5.27) = 0.91

Examples of adjusted monthly $(ET_o - P)_{0.9}$ for April and June:

$(ET_o - P)_{0.9} = 0.65 \times 3.22 = 2.10''$ (for April)

$(ET_o - P)_{0.9} = 0.91 \times 7.52 = 6.84''$ (for June)

Table 5-8. Illustration of development of monthly (ET - P) data for a 90% probability level at Davis.

	Normal-Year Data							90% Probability Level	
	ET_o (Isoline maps) mm/day a/	Inch/ month a/	ET (trees) Inch/ month b/	P Inch/ month c/	ET_o-P Inch/ month d/	ET-P (trees) Inch/ month d/	Adj. Factor, "C" e/	$(ET_o\text{-}P)_{0.9}$ Inch/ month e/	$(ET\text{-}P)_{0.9}$ (trees) Inch/ month e/
Jan	0.85	1.04	1.25	3.88	-2.84	-2.63		-4.00	-3.61
Feb	1.65	1.84	2.21	2.79	-0.95	-0.58		-2.87	-2.59
Mar	2.60	3.17	3.80	1.95	1.22	1.85		-2.02	-1.82
Apr	4.00	4.72	5.66	1.50	3.22	4.16	0.65	2.10	2.99
May	5.30	6.47	7.76	0.51	5.96	7.25	0.91	5.42	6.57
Jun	6.50	7.68	9.22	0.16	7.52	9.06	0.91	6.84	8.22
Jul	6.70	8.18	9.82	0.01	8.17	9.81	0.91	7.43	8.90
Aug	5.70	6.96	8.35	0.03	6.93	8.32	0.91	6.31	7.55
Sep	4.60	5.43	6.52	0.16	5.27	6.36	0.91	4.80	5.77
Oct	3.00	3.66	4.39	1.04	2.62	3.35	0.65	1.71	2.41
Nov	1.40	1.65	1.98	2.04	-0.39	-0.06		-2.10	-1.90
Dec	0.80	0.98	1.18	3.21	-2.23	-2.03		-3.30	-2.98
Total		51.78	62.14	17.28	34.5	44.86		20.31	29.51

a/ Step 1 - in Example 5-3. Data from Isoline maps, Figure 5-11.

b/ Step 2 - k_c for evergreen trees x ET_o.

c/ Step 3 - Table 3, DWR Bull. "California rainfall summary" [14].

d/ Step 4.

e/ Steps 5a. and 5b.

NET WATER USE FOR SYSTEMS INVOLVING ANNUAL CROPS

In the case of wastewater systems involving the growing of annual crops, irrigation system design becomes more complex due to the variation of ET with changing plant cover, stage of growth, and maturity. Clearly a development of normal-year ET on a month-by-month basis is needed. In fact, even shorter periods of time need to be considered during crop development. Once the ET data for a normal year are developed into monthly values, procedures proposed earlier are suggested to arrive at adjusted monthly (ET - P) values for a particular probability level.

Normal-Year ET for Annual Crops

Example 5-4 shows the development of monthly (or 10 to 11-day) ET_o and crop ET data for two annual crops including periods involving land preparation for planting, post harvest, etc. For one crop (tomatoes), two examples are offered, one involving infrequent irrigations during early crop stages and another with very frequent early irrigations. For the former case, and for all periods of full crop cover, crop coefficients as given in Table 5-13 were used in conjunction with ET_o data to estimate ET. For the latter case involving frequent early irrigations, k_c values during early growth stages were developed from a method suggested by Doorenbos and Pruitt [3]. The same method was also used for periods involving land preparation.

The results illustrated in Table 5-9 clearly reveal the reduced water use of annual crops as compared to full cover situations. For example, the estimated normal-year ET for corn (including pre-plant and post harvest periods) was 32.2 inch (81.79 cm) (Apr.-Oct.), whereas ET_o was estimated at 43.2 inch (109.7 cm). An ET of 39.5 inch (100 cm) is predicted for tomatoes (again including pre-plant and post-harvest periods) with a somewhat longer growing season, the use of frequent early irrigations, and with rather high k_c values right up to harvest. This is still almost 4 inches (10.2 cm) less than ET_o, and some 12 inches (20.5 cm) less than the expected ET for evergreen trees for the April through October period.

Example 5-4. Development of normal-year monthly and shorter-period ET_o and crop ET data. Example crops are field corn and processing tomatoes with planting around May 1, and harvest dates of Sept. 10 and 20, respectively.

Step 1. Plot monthly normal-year ET_o data for Mar.-Nov. as in Fig. 5-4 and draw smooth curve through the bar graph which provides a near balancing of areas above and below each monthly mean (ET_o data from Table 5-8).

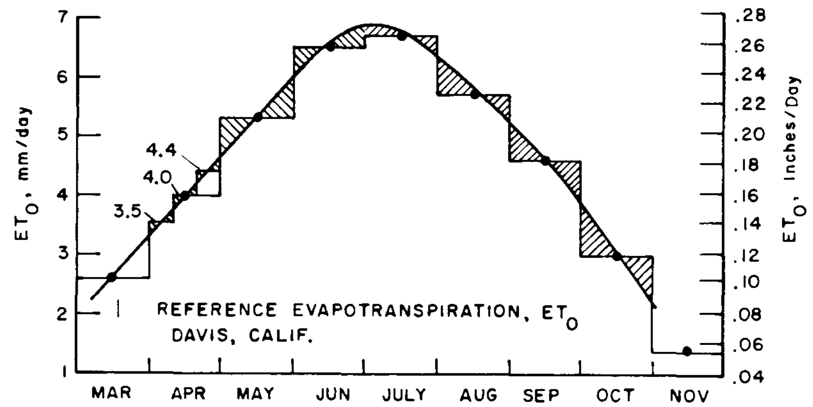

Figure 5-4. Plot of normal-year ET_o, and development of smooth curve (example for Davis).

Step 2. Select ET_o value at the midpoint of each 10 to 11 day period. Tabulate as in Table 5-9 and convert to equivalent total inches in each period.

Step 3. Prepare graph of k_c data as in Fig. 5-5 with data obtained as follows:

a) From Table 5-13 (or Fereres et al., [12, 13]), obtain 10-day planting to harvest k_c data and plot as in Fig. 5-5.

b) For frequent-irrigation cases (< 10-day schedule), select a k_c value for an initial Development Stage (Defined by Doorenbos and Pruitt [3] as "the time during germination or early growth when ground cover is less than 10%".) from Fig. 5-6, and plot as a horizontal line as illustrated in Fig. 5-5 (an estimate of the length in days of the period is obtained from Fig. 5-7). Draw a straight-line extrapolation on up to a tangential meeting with the k_c curve developed from Step 3a). Develop a new curvilinear relationship for k_c from the two straight-line segments.

c) For pre-planting periods, select values of k_c as illustrated in Fig. 5-6 and plot as in Fig. 5-5.

d) For post-harvest periods draw curves of k_c as in Fig. 5-5 reflecting a sharp drop to low values prior to pre-planting periods where soil surfaces are dry.

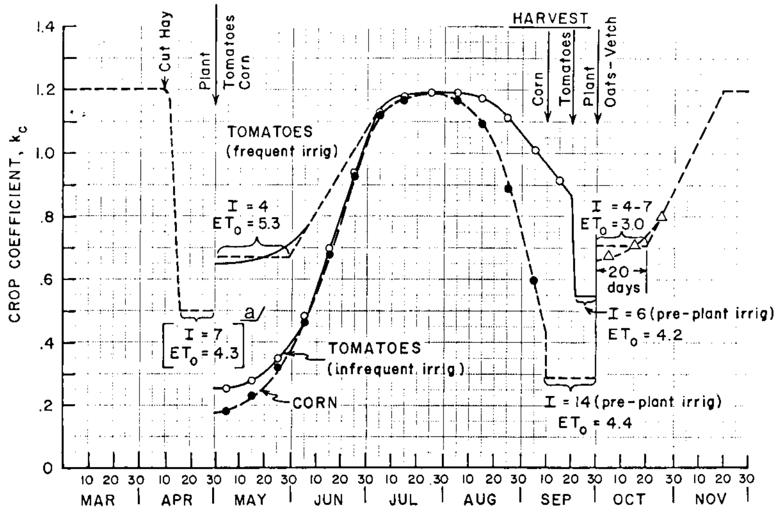

Figure 5-5. Development of crop coefficients for cropping sequences involving a Fall-Winter hay crop of oat and vetch with spring plantings of corn and tomatoes. Both frequent and infrequent early irrigation of tomatoes are illustrated.

a/ I = frequency of irrigation and/or precipitation during period (in days), and ET_o = normal ET_o rate expected midway through the period.

Step 4. From curves developed as in Fig. 5-5, select 10- to 11-day k_c data for each case and tabulate as in Table 5-9.

Step 5. Multiply k_c values by ET_o data to obtain estimates of crop ET and evaporation losses during non-cropped intervals as illustrated in Table 5-9.

Table 5-9. Example of development of normal year monthly and seasonal ET for annual crops. Location – Davis, California. Crops – processing tomatoes (May 1-Sep. 20) and field corn (May 1-Sep. 10) followed by an oat-vetch crop planted Oct. 1 to be harvested for hay around Apr. 5-10.

Month		Normal year ET_o mm/day a/	Normal year ET_o Inch a/	Oat - Corn - Oats k_c b/	Oat - Corn - Oats ET Inch e/	Oats - Tomatoes - Oats k_c b/,c/	ET Inch e/	k_c b/,d/	ET Inch e/
Apr	1-10	3.5	1.38	1.10	1.52	1.10	1.52	1.10	1.52
	11-20	4.0	1.57	0.75	1.18	0.75	1.18	0.75	1.18
	21-30	4.4	1.73	0.50	0.86	0.50	0.86	0.50	0.86
May	1-10	4.8	1.89	0.18	0.34	0.25	0.47	0.65	1.23
	11-20	5.3	2.09	0.23	0.48	0.28	0.59	0.67	1.40
	21-31	5.8	2,52	0.32	0.81	0.35	0.88	0.69	1.74
Jun	1-10	6.2	2.44	0.47	1.15	0.49	1.20	0.77	1.88
	11-20	6.6	2.60	0.68	1.77	0.70	1.82	0.88	2.29
	21-30	6.7	2.64	0.93	2.45	0.94	2.48	1.01	2.67
Jul	1-10	6.8	2.68	1.12	3.00	1.13	3.03	1.13	3.03
	11-20	6.7	2.64	1.17	3.09	1.17	3.09	1.17	3.09
	21-31	6.5	2.80	1.19	3.33	1.19	3.33	1.19	3.33
Aug	1-10	6.2	2.44	1.16	2.83	1.19	2.90	1.19	2.90
	11-20	5.8	2.28	1.09	2.48	1.17	2.67	1.17	2.67
	21-31	5.4	2.32	0.89	2.06	1.11	2.58	1.11	2.58
Sep	1-10	5.0	1.97	0.60	1.18	1.01	1.99	1.01	1.99
	11-20	4.7	1.85	0.29	0.54	0.91	1.68	0.91	1.68
	21-30	4.2	1.65	0.29	0.69	0.55	0.91	0.55	0.91
Oct	1-10	3.6	1.42	0.68	0.97	0.68	0.97	0.68	0.97
	11-20	3.0	1.18	0.71	0.84	0.71	0.84	0.71	0.84
	21-31	2.5	1.08	0.80	0.86	0.80	0.86	0.80	0.86
Total			43.2"		32.2"		35.9"		39.5"

a/ Step 2.
b/ Step 4.
c/ Values of k_c for tomatoes based on infrequent irrigations during early stages of growth.
d/ Values for k_c for tomatoes based on an assumed four-day frequency of irrigation during early stages of growth.
e/ Step 5.

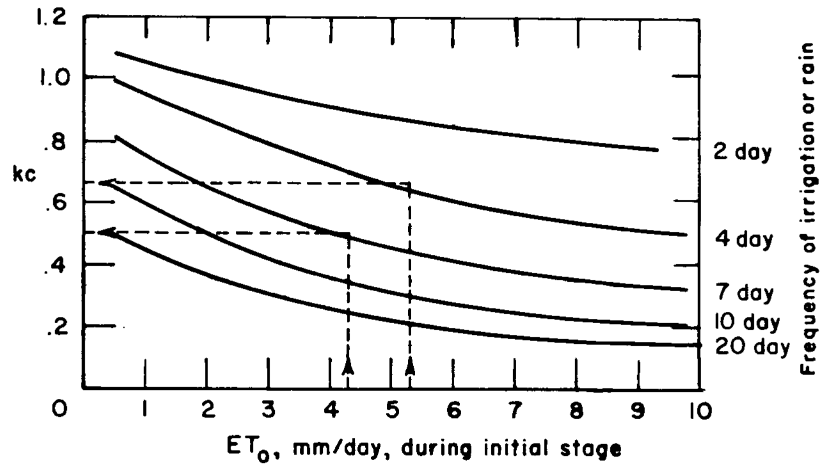

Figure 5-6. Average K_c value for Initial Development Stage as related to level of ET_o and the frequency of irrigation and/or significant rainfall (Adapted from Doorenbos and Pruitt [3]).

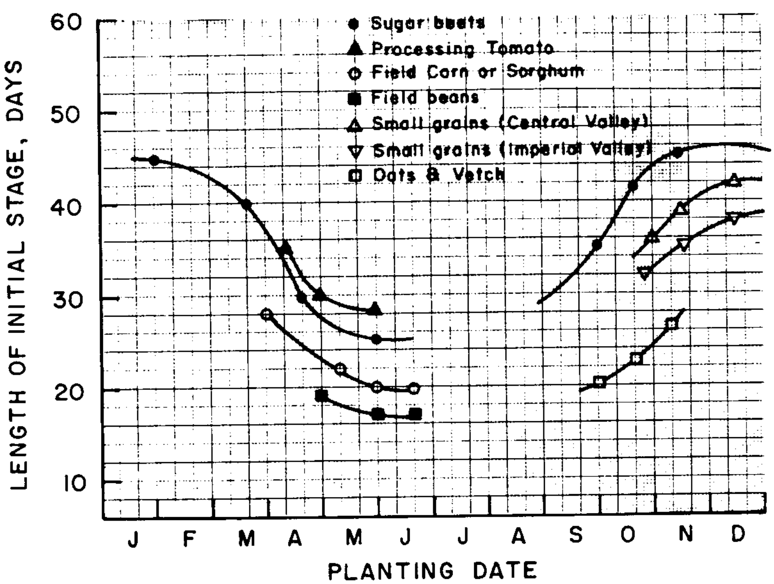

Figure 5-7. Length in days of Initial Development Stage for several annual crops in California as a function of planting date.

Frequency Distribution of Monthly Net Losses

As indicated earlier, development of a month-by-month water balance is usually desirable, and yet the summation of individual month-by-month frequency distribution analyses can be misleading. For cropping patterns involving annual crops, the same procedures as those used in Example 5-3 are suggested for development of adjusted monthly values of (ET - P) at any particular probability level. Thus, in the example for Davis, a "C" of 0.65 would be applied to the transition months of April and October and a "C" of 0.91 for the months of May through September, as in Table 5-8.

Table 5-10 provides an example of cropping sequences using the cases of Example 5-4 but excluding the case for infrequently-irrigated tomatoes. The results depend upon the assumption of a k_c value for December through March of 1.20 for the oat-vetch winter-cover hay crop. Hence, the normal-year and 90% probability data for those months coincide with the data developed in Table 5-8 for evergreen

Table 5-10. Estimated monthly (Losses - Precipitation) at a probability level of 90% (adjusted to provide realistic seasonal and annual levels). Cropping patterns include annual crops with a mix of oats and vetch for winter cover crop, harvested for hay in April.

Month	ET_o Inch[a]	Normal Year ET (Oats, Tomato, Oats) Inch[b]	Normal Year ET (Oats, Corn, Oats) Inch[b]	P Inch	Normal Year ET - P (Oats, Tomato, Oats) Inch	Normal Year ET - P (Oats, Corn, Oats) Inch	Adj. Factor "C" for 90% prob. c	90% Probability $(ET - P)_{0.9}$ (Oats, Tomato, Oats) Inch	90% Probability $(ET - P)_{0.9}$ (Oats, Corn, Oats) Inch
Jan	1.04	1.25	1.25	3.88	-2.63	-2.63	-	-3.61	-3.61
Feb	1.84	2.21	2.21	2.79	-0.58	-0.58	-	-2.59	-2.59
Mar	3.17	3.80	3.80	1.95	1.85	1.85	-	-1.82	-1.82
Apr	4.72	3.56	3.56	1.50	2.06	2.06	0.65	1.34	1.34
May	6.47	4.37	1.63	0.51	3.86	1.12	0.91	3.51	1.02
Jun	7.68	6.84	5.37	0.16	6.68	5.21	0.91	6.08	4.74
Jul	8.18	9.45	9.42	0.01	9.44	9.41	0.91	8.59	8.56
Aug	6.96	8.15	7.37	0.03	8.12	7.34	0.91	7.39	6.68
Sep	5.43	4.58	2.41	0.16	4.42	2.25	0.91	4.02	2.05
Oct	3.66	2.67	2.67	1.04	1.63	1.63	0.65	1.06	1.06
Nov	1.65	1.65	1.65	2.04	-0.39	-0.39	-	-2.10	-2.10
Dec	0.98	1.18	1.18	3.21	-2.03	-2.03	-	-2.98	-2.98
Total								18.90	12.30

a. From Table 5-8.

b. For Apr.-Oct. list monthly totals obtained from 10-11 day data in Table 5-9. For Nov. assume ET for oats-vetch is equivalent to ET_o, and for Dec.-Mar., that ET is equivalent to ET(trees) as in Table 5-8.

c. Same as in Table 5-8.

trees. For November, Figure 5-5 reveals an average k_c for the month a little above 1.0. A conservative estimate would be the use of 1.0 for k_c; hence for November, the ET_o value for that month is used directly in Table 5-10.

The annual summary of the 90% probability level for ET - P indicates values of 18.9 and 12.3 inches (48.0 and 32.2 cm) for the frequently-irrigated tomato and corn crops, respectively, when a winter cover crop of oats and vetch are involved. This compares with 29.5 and 20.3 inches for continuous cropping of evergreen trees and well-managed pasture, respectively, at the 90% probability of exceedance level (See Table 5-7).

PEAK ET DEMAND FOR IRRIGATION SYSTEM DESIGN

For optimal crop production, irrigation systems should be designed to meet crop needs during expected levels of peak ET. Prior discussion has revealed the wide year-by-year variation of actual ET_o. The variation of ET during peak demand months is expected to be even greater. For example, the frequency analysis of lysimeter records for Davis indicates that a monthly total for June as great as 8.85 inches (22.48 cm) is expected with a 90% probability in any one year, 14% higher than the mean monthly loss for June of 7.76 inches (19.71 cm) . However, except for very deep-rooted crops growing in medium- to heavy-textured soils, the level of depletion allowable under peak-demand conditions would normally be much less than this. More typical for optimal crop production would be 3 to 5 inches (7.62 to 12.7 cm) of depletion, or even less for shallower-rooted crops, lighter-textured soils, or crops otherwise benefitting from frequent irrigations. Hence, for the shorter consecutive-day periods involved, peak loss design rates can be expected to run well above long-time monthly means for peak demand months.

Jensen and Criddle [10] provided a design approach involving the selection of a multiplying factor to use with the long-time mean monthly ET to obtain a peak design value for any given level of soil water depletion. This approach was later adapted by Doorenbos and Pruitt [3] and still later by Pruitt et al. [4] for California. Procedures in the last report were based on data for extreme maximum values of evaporation (or E_o) at selected stations in California and adjacent states as published by Bassett and Jensen [11]. Extreme maximum values of ET_o were derived by normalizing E_o data for a two-year occurrence frequency against the normal-year July ET_o as obtained from the ET_o isoline maps of Pruitt et al. [3]. Figure 5-8 in Example 5-5 reproduces the results for several locations in California representing a wide range of climatic conditions. By locating the desired level of soil moisture depletion on the x-axis, one can select a ratio which when multiplied by the normal-year ET_o for the peak demand month, will provide peak ET_o data for either an average 5-year or 10-year expected occurrence frequency. For crops other than grass and if they are under full-cover conditions during peak demand periods, the k_c for that crop should also be applied (see Table 5-2 or 5-13).

Example 5-5 outlines the use of Figure 5-8 in development of design peak ET rates (based on a 10-year frequency). In addition to data in Figure 5-8, input data needed to calculate the time of expected peak ET include the following: 1) effective rooting depth of crop; 2) an estimate of total available water (TAW) in effective root zone; and 3) an estimate of readily available water (RAW), or of management allowed deficit (MAD) in the effective root zone. TAW, RAW and MAD represent terminology proposed by Merriam and Keller [25].

While the design data developed in Table 5-11 would provide an irrigation system with full capacity to meet possible short-term peak ET demand with a 90% probability (on the average for nine out of ten years), economic considerations may call for a reduction in the design estimates. This would be particularly true for soils with moderate to high values of TAW and RAW. Water stored in the root zone beyond that normally described as "readily available", may, for such soils, contribute substantially in coping with unusual ET demands. Hence, a system with a capacity to meet ET demands somewhat less than the design values of Table 5-11 may be considered. If, however, the designer chooses such an option, special attention will be needed in irrigation operations, to ensure that the peak demand periods are entered into with a fully recharged soil profile.

Example 5-5. Illustration for Davis, California of Development of design peak ET rates for several crops.

Step 1. From local soils and crop data, e.g., as obtained from Cooperative Extension Farm Advisors or Soil Conservation Service technicians, list values of effective rooting zone, TAW, and RAW (as defined earlier) for period of peak evaporative demand.

Step 2. Enter Fig. 5-8 on the X-axis at a value equal to the RAW or MAD in mm and project vertically to intersect a curve most likely to represent the project site involved.

Obtain a value for the ratio of mean peak ET_o to normal-year mean monthly ET_o by projecting horizontally from the intersect point back to the Y-axis.

Step 3. For crops involved, list as in Table 5-11, the normal-year mean monthly ET values for the month of peak use (normally July in California). ET_o is assumed to be equivalent to pasture ET (Data obtained directly from Table 5-9, or calculated from data contained therein).

Step 4. Multiply "ratio" by July normal-year ET values.

Table 5-11. Example development of design peak ET rates for several crops (10-year frequency).

Crop	Effective rooting depth, ft.[a]	TAW in.[a]	RAW or MAD[a] at peak-demand period in.	mm	Ratio, Fig. 5-8 b	Normal-Year[c] July mean monthly ET mm/day	inch/day	Design ET[d] (10-year frequency) inch/day
Pasture	3.0	6.0	3.0	75	1.30	6.7	.264	.343
Tomatoes	5.0	10.0	5.0	125	1.22	8.0	.315	.384
Corn	4.0	8.0	4.0	100	1.25	7.8	.307	.384

a. Step 1.

b. Step 2 - From Figure 5-8.

c. Step 3 - Data from Table 5-9.

d. Step 4.

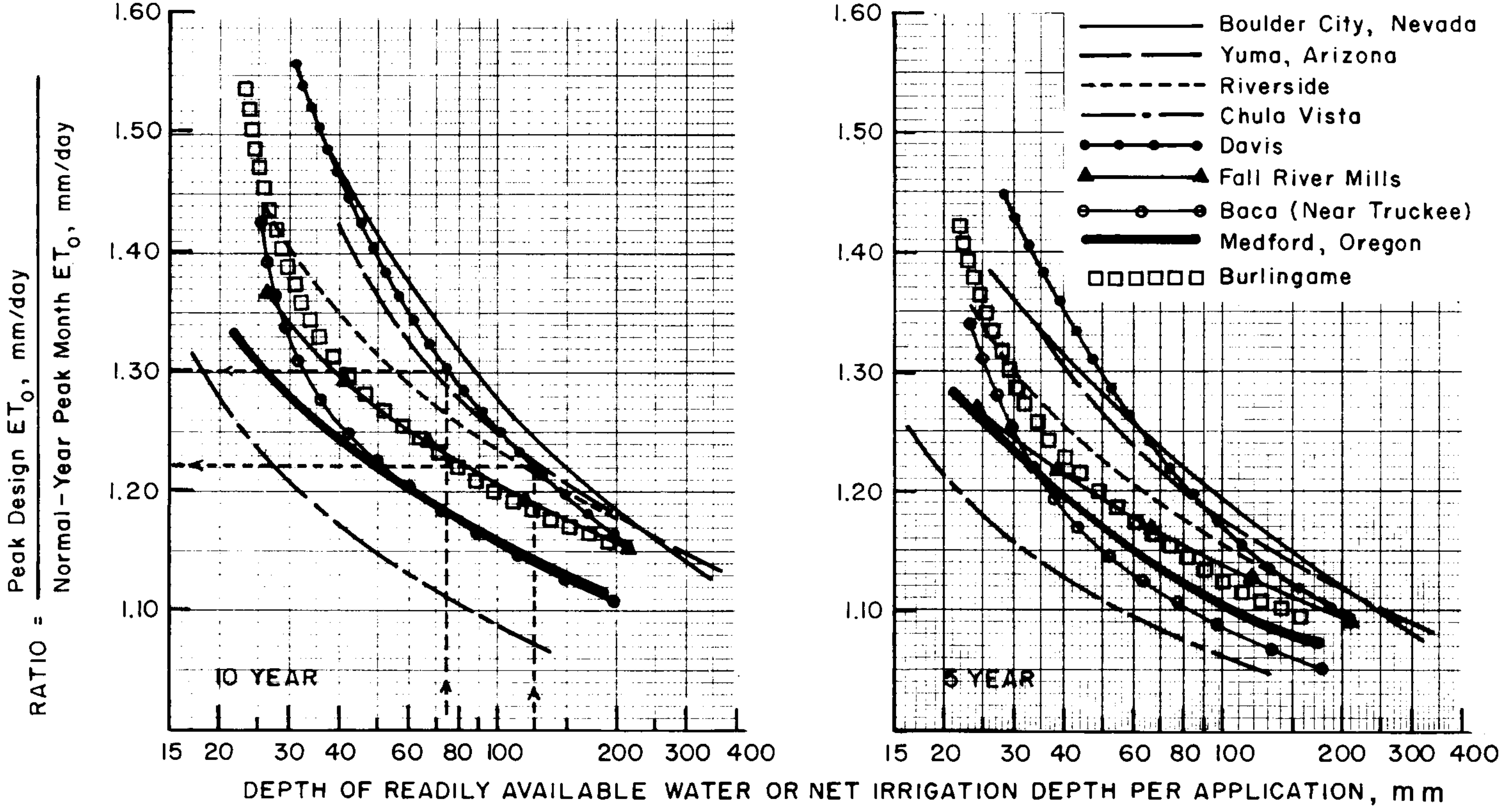

Figure 5-8. Examples for California and bordering state locations of the ratio of design peak ET_o to normal-year ET_o (July) as a function of readily available soil water or net irrigation application based on analyses of Bassett and Jensen [11].

ADDITIONAL TABLES AND FIGURES

Table 5-12. Recommended monthly crop coefficients, k_c for principal crops grown in California, as adapted from Table 5 of DWR Bull. 113-3 [7][a]. Values of k_c for relating to ET_o were derived by dividing DWR's monthly k_p data for the month and crop of interest, by the k_p for pasture for the same month. Example: Cantaloupes in June; k_c = 0.86/0.78 = 1.10.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Field Crops												
Alfalfa (hay)	1.00	1.00	0.92	0.91	0.91	0.94	0.97	1.03	1.04	1.03	1.00	1.00
Barley (fall)	0.94	1.28	1.08	0.65	0.26	-	-	-	-	-	0.14	0.43
Barley (winter)	0.42	0.91	1.25	1.06	0.64	0.26	-	-	-	-	-	-
Beans (dry)	-	-	-	-	-	-	0.54	1.09	0.56	-	-	-
Cantaloupes	-	-	-	0.19	0.41	1.10	0.17	-	-	-	-	-
Corn (field)	-	-	-	-	0.15	0.62	1.20	1.08	0.65	-	-	-
Cotton (solid)	-	-	-	-	0.13	0.69	1.31	1.29	1.13	0.65	-	-
Cotton (2 x 1)	-	-	-	-	0.13	0.63	1.17	1.36	1.13	1.01	-	-
Cotton (2 x 2)	-	-	-	-	0.13	0.47	1.13	1.18	1.08	0.55	-	-
Cotton (2 x 2)[b]	-	-	-	-	0.13	0.19	0.87	1.13	0.81	0.35	-	-
Grain sorghum	-	-	-	-	0.13	0.32	1.15	1.05	0.52	-	-	-
Pasture (improved)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rice	-	-	-	1.04[c]	1.15	1.28	1.28	1.28	1.17	0.40	-	-
Sugar beets (annual)	-	-	-	0.20[d]	0.50	1.00	1.18	1.03	1.04	0.79	0.55	-
Sugar beets (overwintered)	1.00	1.00	1.00	0.49	0.20[d]	0.50	1.00	1.18	1.04	1.07	1.00	1.00
Tomatoes (Machine harvested)	-	-	-	0.29	0.77	1.13	1.06	0.79	-	-	-	-
Trees and Vines												
Deciduous orchard[e]	-	-	0.59	0.71	0.83	0.90	0.96	0.96	0.91	0.80	-	-
Subtropical orchard[f]	-	-	0.59	0.58	0.64	0.64	0.64	0.64	0.58	0.60	-	-
Vineyard (table grapes)	-	-	-	0.16	0.58	0.77	0.85	0.83	0.71	0.40	-	-
Vineyard (wine grapes)[f]	-	-	-	0.16	0.58	0.71	0.64	0.45	0.26	0.07	-	-
Truck Crops												
Potatoes (Spring crop)	-	-	0.66	1.08	1.20	0.64	-	-	-	-	-	-
Tomatoes (hand-picked)	-	-	0.29	0.78	1.13	1.13	0.96	0.64	0.39	-	-	-

a. Relate mainly to Central Valley (California) growing seasons. Modifications may be needed for use in areas or situations with different planting dates.

b. For extremely fine textured (clay) soils.

c. Planted or harvested at mid-month. ET_o for partial month should be used with ratio.

d. Adjusted upward from original values which appeared to be unreasonable.

e. Deciduous trees except almonds (Presumably clean cultivated orchards). Coefficients should likely be 10-25% lower for almonds during the last one-third of the season if cultural practices involve no post-harvest irrigations.

f. No ET data available (in 1974). Original k_p ratios reported were estimated from PET data modified to reflect prevalent irrigation and cultural practices.

Table 5-13. Recommended 10-day crop coefficients, k_c for a number of selected crops grown in various regions of the State[a] (See Figure 5-9 for a delineation of regions.)

	Processing tomatoes					Sugar beets[b]				Grain corn			Milo
Plant Date	2/1	3/1	4/1	5/1	6/1	4/1	5/1	6/15	10/1	3/15	5/1	6/15	5/15
Harvest Date	6/30	8/10	9/10	9/30	11/20	10/20	11/20	3/20	6/30	8/15	9/10	10/15	9/30
Jan 1-10								1.17	1.16				
11-20								1.16	1.17				
21-31								1.15	1.17				
Feb 1-10	0.36							1.14	1.17				
11-20	0.40							1.13	1.17				
21-28	0.42							1.12	1.17				
Mar 1-10	0.48	0.26						1.11	1.16				
11-20	0.57	0.26						1.10	1.15	0.17			
21-31	0.72	0.26							1.14	0.19			
Apr 1-10	0.92	0.27	0.26			0.15			1.13	0.23			
11-20	1.03	0.29	0.26			0.18			1.11	0.32			
21-30	1.08	0.34	0.27			0.25			1.09	0.46			
May 1-10	1.10	0.46	0.29	0.25		0.34	0.21		1.05	0.65	0.18		
11-20	1.10	0.65	0.35	0.28		0.49	0.23		1.02	0.99	0.23		0.13
21-31	1.06	0.92	0.47	0.35		0.74	0.28		0.97	1.15	0.32		0.17
Jun 1-10	0.98	1.10	0.67	0.49	0.22	0.97	0.44		0.91	1.19	0.47		0.21
11-20	0.88	1.17	0.93	0.70	0.24	1.08	0.65	0.22	0.84	1.20	0.68	0.30	0.28
21-30	0.76	1.19	1.12	0.94	0.27	1.13	0.87	0.24	0.80	1.19	0.93	0.35	0.40
Jul 1-10		1.16	1.17	1.13	0.30	1.16	1.06	0.30		1.05	1.12	0.58	0.82
11-20		1.09	1.19	1.17	0.40	1.17	1.11	0.47		1.04	1.17	1.01	1.08
21-31		0.97	1.16	1.19	0.54	1.17	1.16	0.80		0.87	1.19	1.18	1.12
Aug 1-10		0.86	1.07	1.19	0.72	1.17	1.17	1.09		0.65	1.16	1.20	1.12
11-20			0.97	1.17	0.93	1.16	1.18	1.15		0.52	1.09	1.21	1.10
21-31			0.86	1.11	1.03	1.14	1.18	1.18			0.89	1.21	1.06
Sep 1-10			0.73	1.01	1.12	1.12	1.18	1.19			0.60	1.04	0.95
11-20				0.91	1.16	1.10	1.18	1.20				0.95	0.85
21-30				0.60	1.19	1.08	1.18	1.21				0.78	0.72
Oct 1-10					1.19	1.06	1.18	1.21	0.36			0.56	
11-20					1.15	1.03	1.18	1.21	0.40			0.35	
21-31					1.07		1.17	1.21	0.44				
Nov 1-10					0.96		1.16	1.21	0.55				
11-20					0.82		1.15	1.21	0.70				
21-30								1.20	0.90				
Dec 1-10								1.19	1.04				
11-20								1.18	1.10				
21-31								1.18	1.15				
Regions where applicable	10,11	4,5,6,8,9,10			9,10	4,5,6,8			11	5	4,5, 6[c],8[c]	5	4,5, 6[c],8[c]

a. Adapted from recommendations for the Sacramento and San Joaquin Valleys as developed from many studies including those cited herein [3, 6, 7, 15, 16]. Extension to other regions (as delineated in Figure 5-9) assume that during growth stages involving full ground cover, k_c values would be similar in all areas of the state except for the Imperial Valley in Region 11 where soil salinity and very high evaporative demands apparently combine to produce lower than expected k_c's at least for cotton. Region 11 coefficients were largely adapted from studies conducted by the Imperial Valley Conservation Research Center at Brawley [26, 27].

b. Planting and harvest dates vary widely for sugar beets.

c. Season can extend 20-40 days longer in Regions 6 and 8 than that indicated.

Table 5-13. Continued

	Cotton			Field beans		Wheat & Barley			Sudan grass	Deciduous orchards with cover		Rice	
Plant Date	4/1	4/20	4/1	5/1	6/1	11/20	12/1		4/1			4/1	4/1
Harvest Date	9/30	10/15	10/31	8/20	9/20	6/20	5/31		8/20			9/30	8/31
Jan 1-10						0.60	0.45						
11-20						0.77	0.54			0.90	0.50		
21-31						0.93	0.62						
Feb 1-10						1.05	0.76						
11-20						1.13	0.90			0.95	0.45		
21-28						1.17	0.98						
Mar 1-10						1.19	1.04						
11-20						1.20	1.07			1.05	0.60		
21-31						1.20	1.10						
Apr 1-10	0.12		0.27			1.20	1.10		0.58				1.00
11-20	0.15		0.30			1.19	1.09		0.68	1.15	1.00		1.02
21-30	0.17	0.15	0.34			1.18	1.05		0.80				1.04
May 1-10	0.21	0.17	0.38	0.17		1.15	0.85	0.35	0.91			1.00	1.06
11-20	0.28	0.20	0.43	0.21		1.10	0.58	0.51	1.04	1.20	1.10	1.02	1.12
21-31	0.41	0.26	0.48	0.40		1.00	0.35	0.67	1.08			1.05	1.18
Jun 1-10	0.59	0.41	0.55	0.80	0.12	0.87		0.98	1.10			1.08	1.20
11-20	0.79	0.62	0.63	1.10	0.17	0.57		1.09	1.10	1.20	1.20	1.14	1.20
21-30	1.05	0.82	0.67	1.15	0.41			1.18	1.10			1.18	1.20
Jul 1-10	1.18	1.08	0.70	1.14	0.83			1.19	1.10			1.20	1.20
11-20	1.22	1.18	0.73	1.08	1.09			1.15	1.10	1.20	1.20	1.20	1.20
21-31	1.22	1.22	0.74	0.95	1.14			1.02	1.10			1.20	1.20
Aug 1-10	1.22	1.22	0.74	0.75	1.15			0.82	1.10			1.20	1.15
11-20	1.22	1.22	0.75	0.52	1.14			0.58	1.10	1.20	1.20	1.20	1.10
21-31	1.15	1.18	0.76		1.06							1.18	1.00
Sep 1-10	1.00	1.13	0.76		0.78							1.12	
11-20	0.83	0.96	0.76		0.45					1.15	1.15	1.00	
21-30	0.65	0.82	0.74									0.90	
Oct 1-10		0.62	0.62										
11-20		0.46	0.50							1.05	1.00		
21-31			0.45										
Nov 1-10													
11-20										1.00	0.85		
21-30						0.24							
Dec 1-10						0.30	0.31						
11-20						0.38	0.35			0.95	0.60		
21-31						0.49	0.40						
Regions where applicable	5	5	11[d]	5	4,5	4,5	11[d]	3[e]	11[d]	4,5[f]	2,3, 7[g]	4[h]	5[h]

d. k_c data suggest significant control of transpiration for cotton grown at Brawley. As compared to cotton grown in the San Joaquin Valley [7], in Arizona [28, 29], and in Israel [30, 31], coefficients in July and August are very low. Somewhat lower k_c's are also suggested for grains and Sudan grass.

e. Would also apply to Regions 2 and 7 in mountain valley areas where small grains are grown.

f. Mature trees with year-around dense green cover crop.

g. Same as f., but with dormant cover crop during winter months due to heavy frosts.

h. Rice grown in areas with a very high percentage of surrounding land also planted to rice, may need 10-15% lower k_c values (Lourence and Pruitt [32]).

Table 5-14a. Risk of at least one occurrence of a rare event for various design periods in years versus probabilities of occurrence within a year.

Probability %	Design Period (years) 5	10	15	20	25	30	35	40	45
95	0.226	0.401	0.537	0.642	0.723	0.785	0.834	0.871	0.901
90	0.409	0.651	0.794	0.878	0.928	0.958	0.975	0.985	0.991
85	0.556	0.803	0.913	0.961	0.983	0.992	0.994	0.997	0.999
80	0.672	0.893	0.965	0.988	0.996	0.999			
75	0.763	0.944	0.987	0.997	0.999				
70	0.832	0.972	0.995	0.999					
65	0.884	0.987	0.998						
60	0.922	0.994							
55	0.950	0.997							

Table 5-14b. Risk of at least two occurrences of a rare event for various design periods in years versus probabilities of occurrence within a year.

Probability %	Design Period (years) 5	10	15	20	25	30	35	40	45
95	0.023	0.086	0.171	0.264	0.358	0.446	0.528	0.601	0.665
90	0.081	0.264	0.451	0.608	0.729	0.816	0.878	0.920	0.948
85	0.165	0.456	0.681	0.824	0.907	0.952	0.976	0.988	0.994
80	0.263	0.624	0.833	0.931	0.973	0.989	0.996	0.999	1.000
75	0.367	0.756	0.920	0.976	0.993	0.998	1.000		
70	0.472	0.851	0.965	0.992	0.998	1.000			
65	0.572	0.914	0.986	0.998	1.000				
60	0.663	0.954	0.995	0.999	1.000				
55	0.744	0.977	0.998	1.000					

Table 5-14c. Risk of at least three occurrences of a rare event for various design periods in years versus probabilities of occurrence within a year.

Probability %	Design Period (years) 5	10	15	20	25	30	35	40	45
95	0.002	0.011	0.036	0.075	0.127	0.187	0.254	0.323	0.392
90	0.008	0.070	0.184	0.323	0.463	0.588	0.694	0.778	0.841
85	0.027	0.180	0.395	0.595	0.746	0.849	0.913	0.952	0.973
80	0.058	0.322	0.602	0.794	0.902	0.955	0.981	0.993	0.997
75	0.103	0.474	0.764	0.909	0.968	0.989	0.997		
70	0.163	0.618	0.873	0.964	0.991	0.998			
65	0.236	0.738	0.938	0.988	0.998				
60	0.317	0.833	0.973	0.996	1.000				
55	0.407	0.901	0.989	0.999					

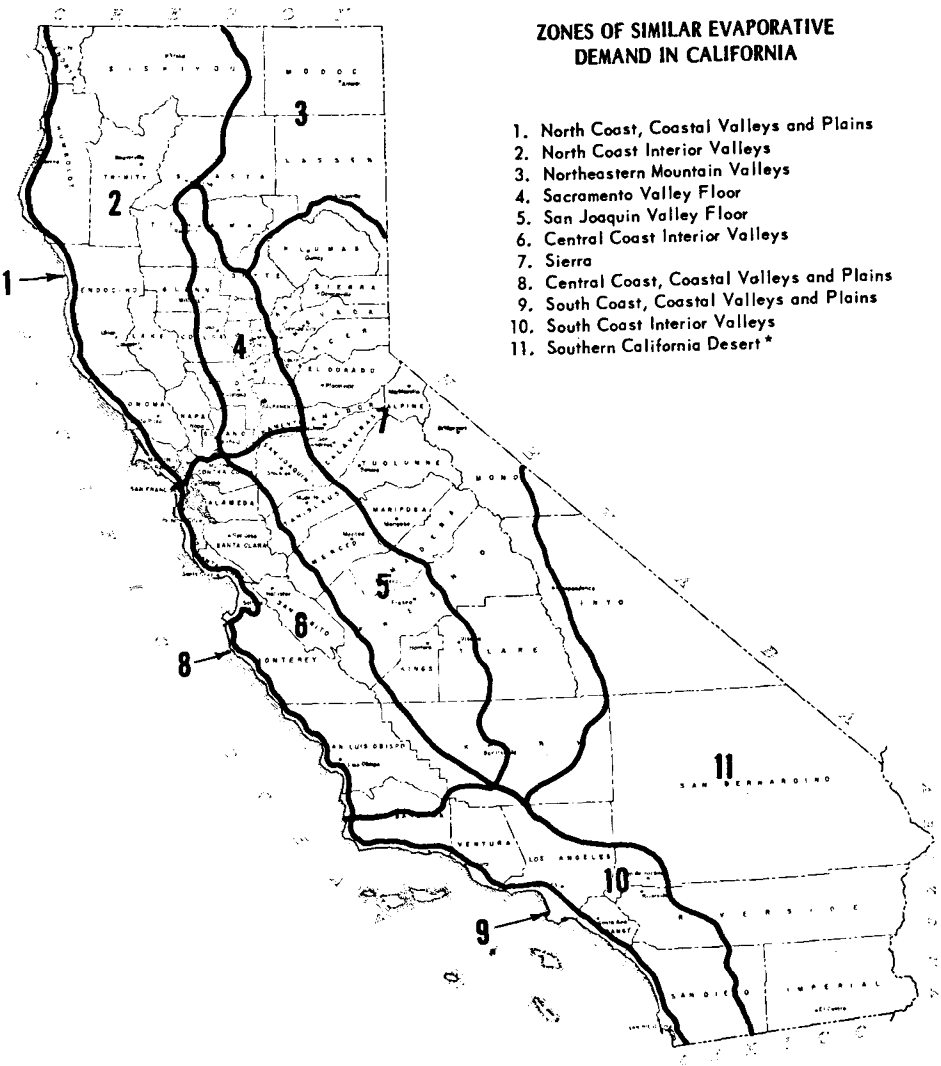

Figure 5-9. Zones of similar evaporative demand. After California DWR Bull. 113-3 [7].

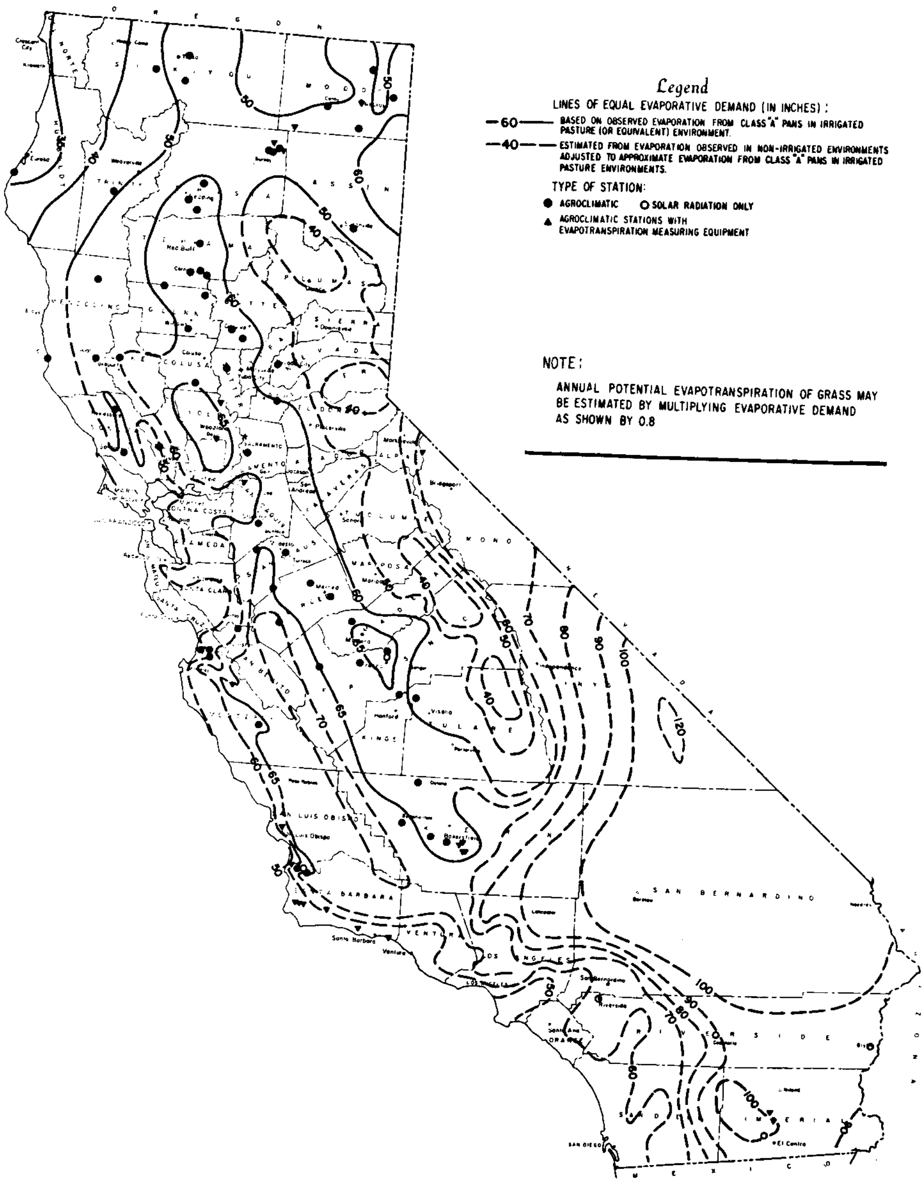

Figure 5-10. Annual evaporative demand in California, the expected evaporation loss in inches (for normal conditions) from a National Weather Service Class "A" pan located in an irrigated pasture (or comparable environment). After California DWR Bull. 113-3 [7].

Figure 5-11. Average daily reference evapotranspiration, ET_0 in mm per day for normal conditions. See Pruitt et al. [4], for larger scale maps.

Figure 5-11. (Continued)

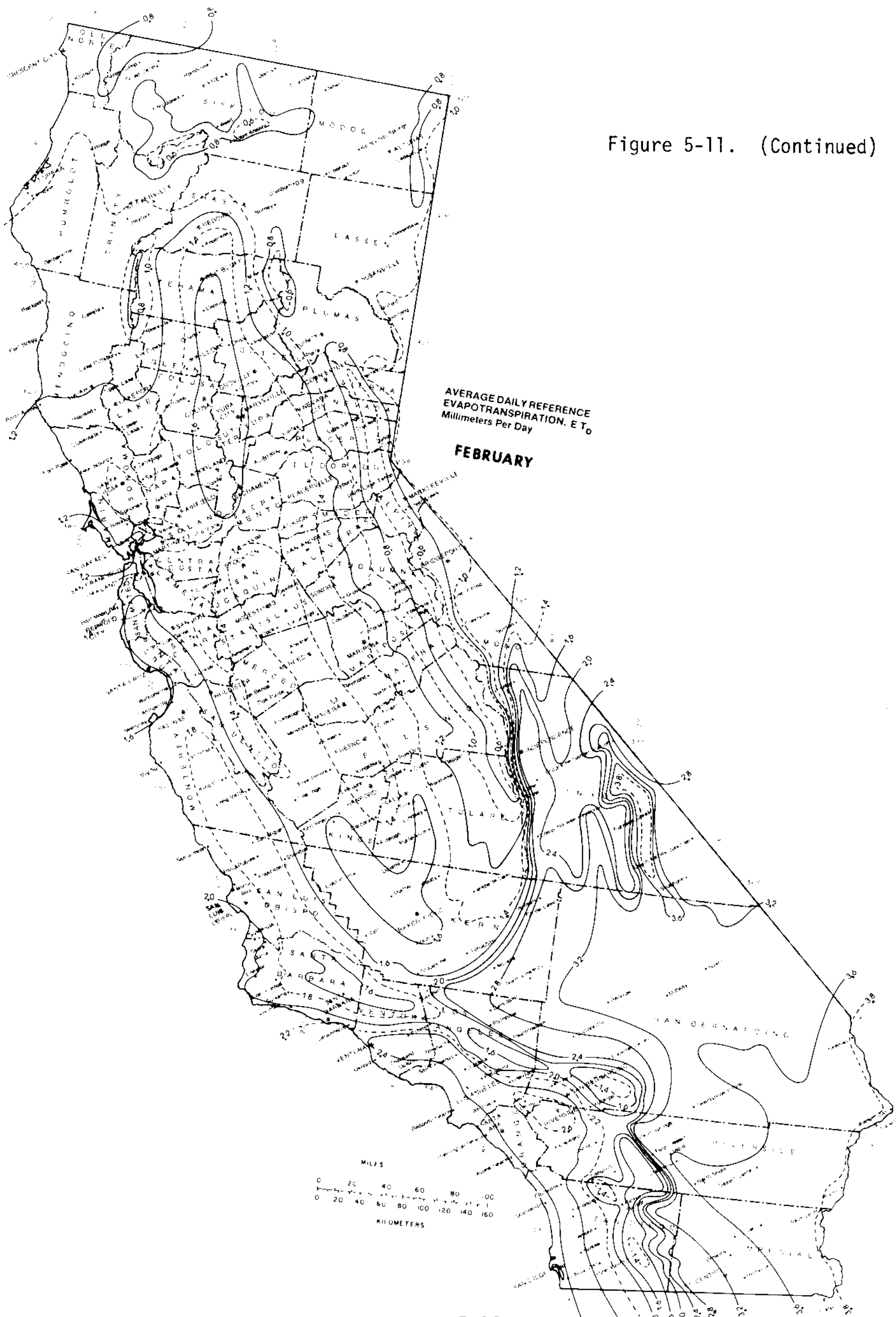

Figure 5-11. (Continued)

Figure 5-11. (Continued)

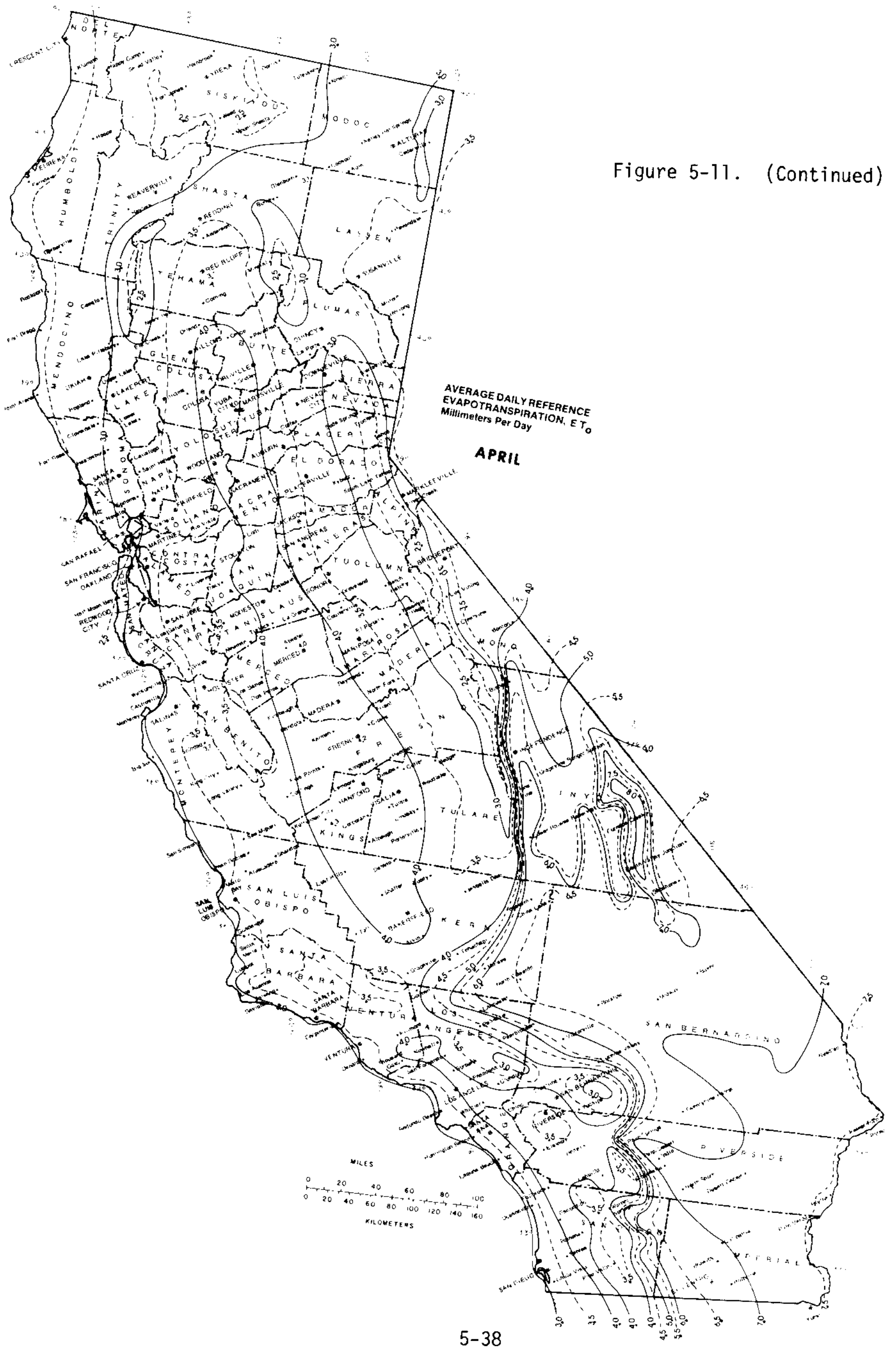

Figure 5-11 (Continued)

Figure 5-11 (Continued)

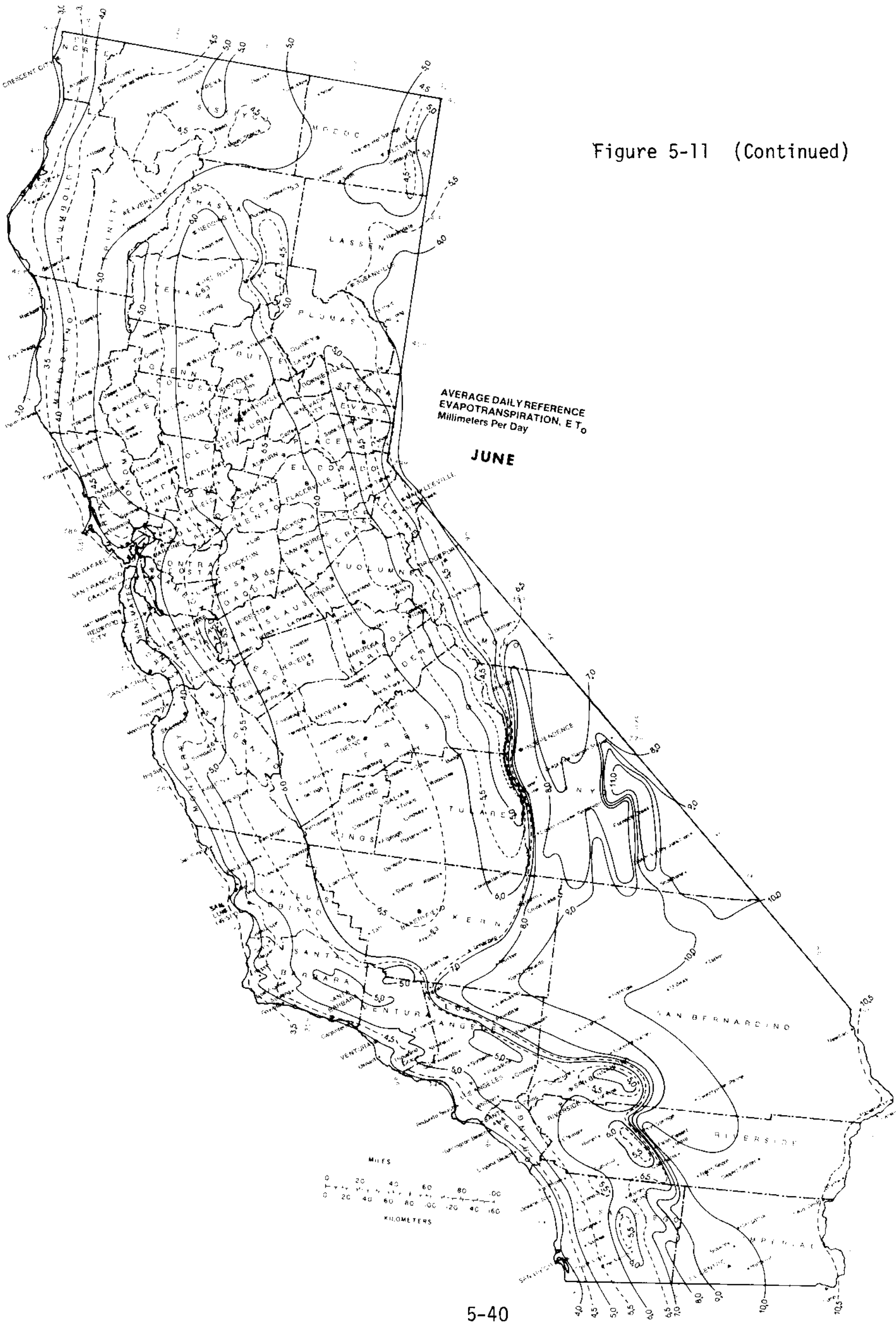

Figure 5-11 (Continued)

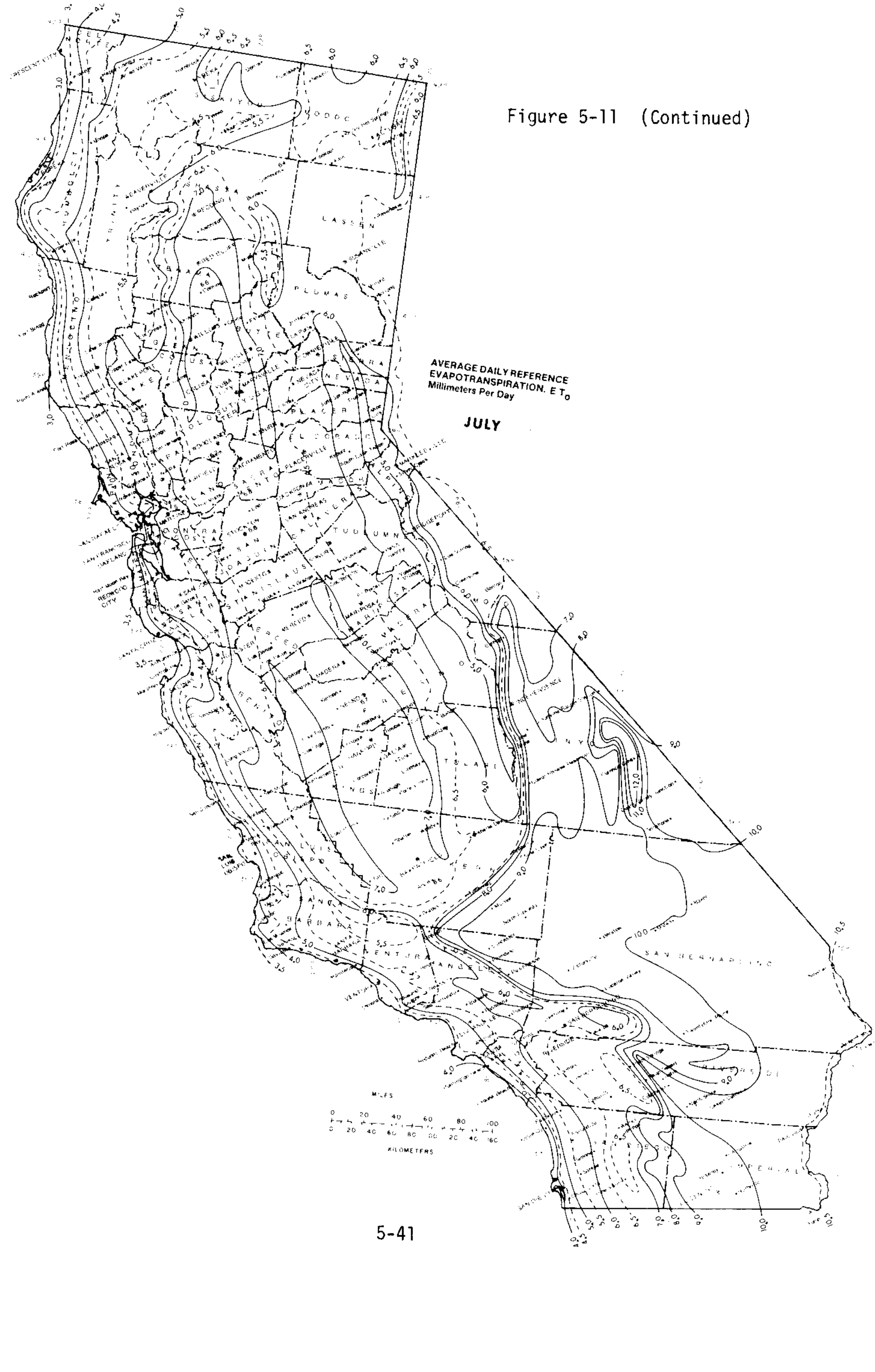

Figure 5-11. (Continued)

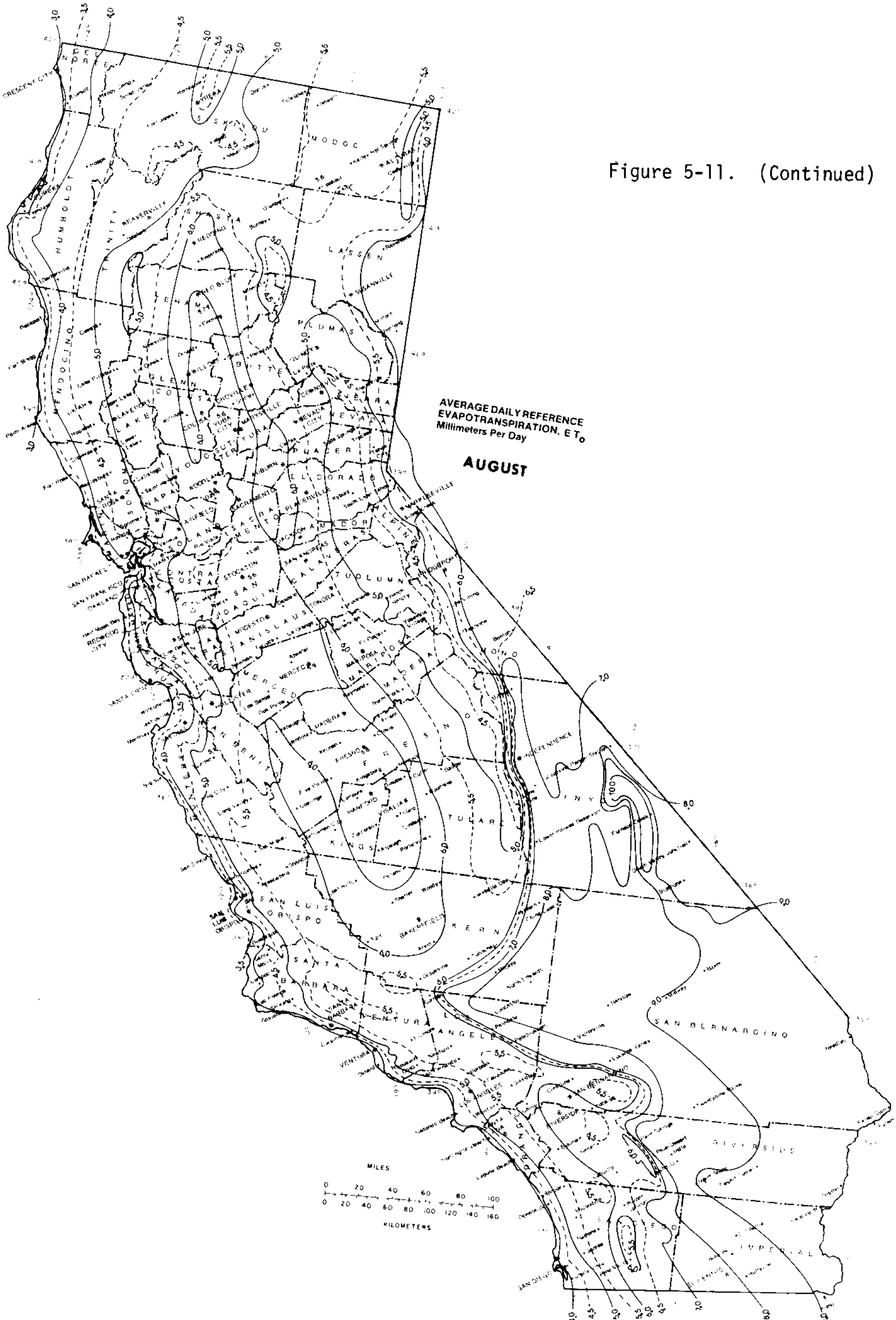

Figure 5-11 (Continued)

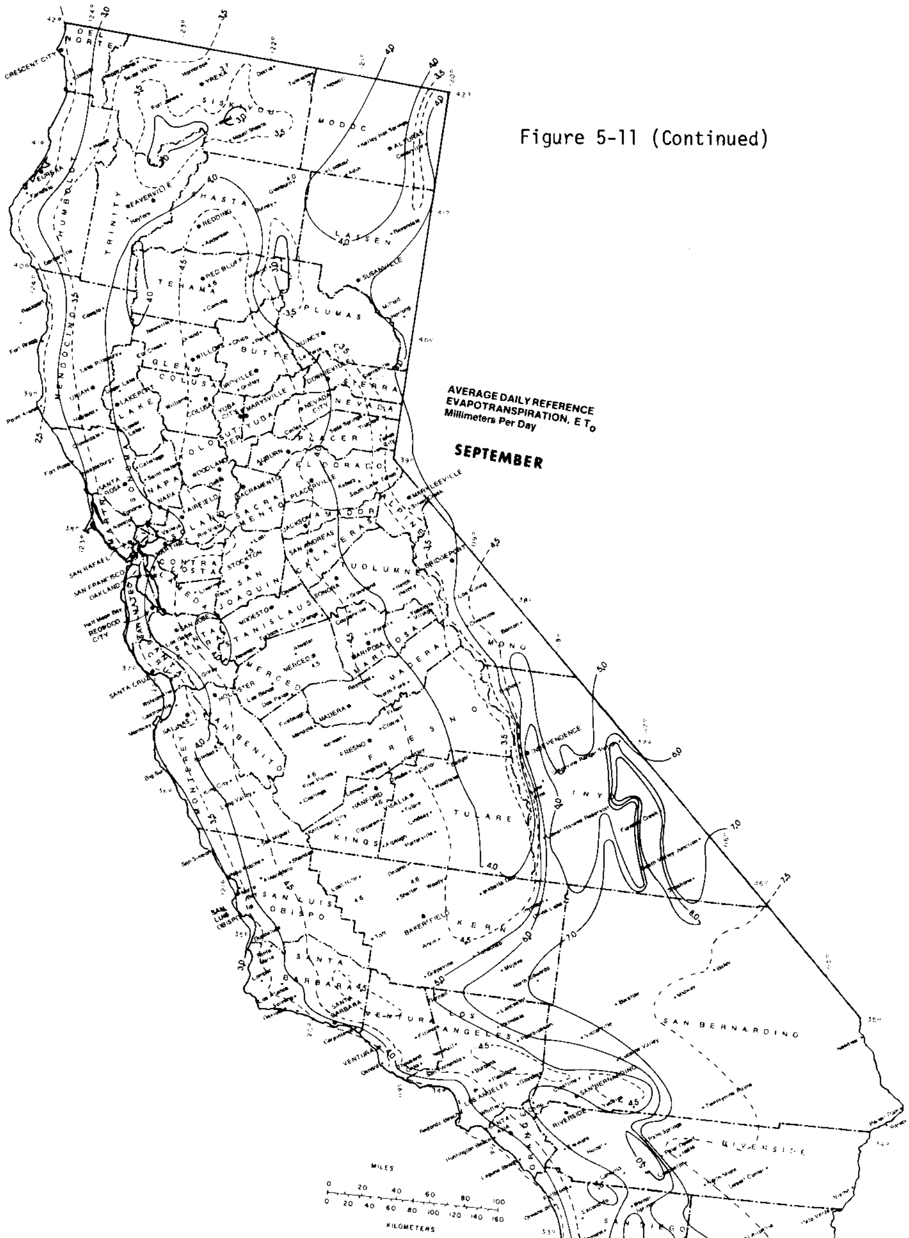

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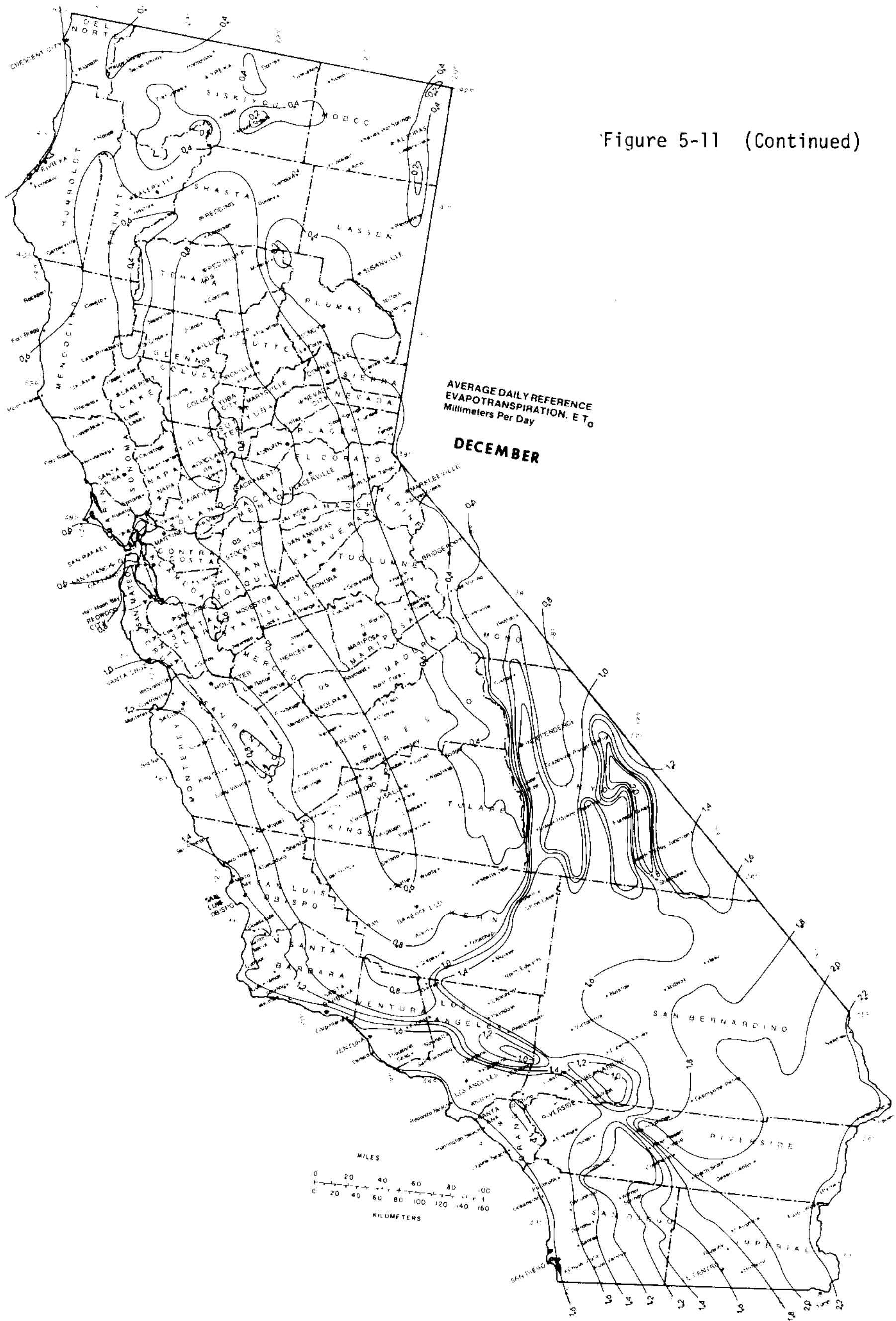
Figure 5-11 (Continued)

Figure 5-11 (Continued)

Figure 5-11 (Continued)



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CHAPTER 6

CROP SELECTION AND MANAGEMENT

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INTRODUCTION

The choice of crop species to be irrigated will influence the type of water distribution system selected and the timing and depth of irrigation water applied. In choosing the crop, a farmer is influenced by economics, climate, soil and water characteristics, management skill, labor and equipment availability, and tradition. If reclaimed wastewater is substituted for a fresh water source, additional constraints are introduced. The degree to which the use of wastewater influences crop selection depends on the goals of the user and the treatment plant designers and on the wastewater properties. If the main objective is to produce a profitable crop on the maximum number of acres, and if the water quality is satisfactory according to agricultural criteria, then the use of wastewater will not greatly affect the choice of crop species. Where water quality is limiting or where other objectives intrude (such as wastewater disposal), the use of wastewater can greatly influence the selection of plant species.

At many wastewater irrigation sites in California, the objective is not exclusively either (1) crop production on the greatest possible land area or (2) disposal/land treatment, but rather a mixture of the two. This is sometimes the case where the treated wastewater is used to irrigate crops growing on land owned by the treatment district. In that case, the farmer's ability to profitably farm the land may be restricted by the availability of land area and off-line storage. Also, in some cases, the farm may be operated by treatment district employees, and thus management skill is limited. Depending on the severity of these constraints, the crop of choice may be a perennial forage even if it would not be the most profitable crop in the absence of the constraints imposed by the use of wastewater. Again, when water quality, management skills, and land area available are adequate, selection criteria will not differ greatly between sites irrigated with wastewater and fresh water.

This chapter presents a summary of crop selection criteria, with emphasis on selection and management of perennial forage species. Crop selection for slow rate land treatment systems in the U.S. has been discussed in other publications [1,2,3]. The following discussion is limited to California conditions.

CROP SELECTION CRITERIA

The factors affecting selection of plant species discussed here are governmental regulations, crop tolerance of salts and specific ions, management requirements, crop uptake of nitrogen and phosphorus, crop use of water, economic value of the crop, climate, and soil physical characteristics.

Regulatory Requirements

Current regulations in California require that some degree of pretreatment be used wherever wastewater is reclaimed. Wastewater treated only to the primary level can be used to irrigate fodder, fiber, and seed crops (but not pasture for milking animals) and can be used for surface irrigation of orchards and vineyards. Wastewater treatment required for landscaping irrigation depends on the degree of public contact. For example, landscaping on parks and playgrounds requires wastewater oxidation, coagulation, clarification, filtration, and disinfection, while landscaping in cemeteries and golf courses does not require water treated to such a high degree. Wastewater treatment and quality criteria for irrigation are summarized in Table 10-3 (p. 10-20) and are presented in more detail in Appendix F (see particularly Articles 2, 3 and 4).

Tolerance of Saline and High-Boron Conditions

A high salt content and high boron content of soil and/or water can affect the selection of crop species. The main effect soil salinity has on crops is to make it difficult for roots to take up water. The saltier the soil, the less readily available is the water. In appearance, grasses and forage legumes on saline soils are very much like plants experiencing water stress. They are stunted and bear small leaves that generally have a dark, blue-green color rather than the bright green of plants that have an adequate moisture supply. If the soil water is too saline, the plants will eventually turn brown and die, usually as the result of extreme moisture deficiency rather than any toxic effect of salinity. Leaching of salt from soil and selection of crop species are the two methods used (usually in combination) to manage excessively saline water.

Plant species differ markedly in their tolerance to excessive concentrations of boron. Boron in water is toxic to some plant species at very low concentrations (ca. 1 mg/L). In areas where boron tends to occur in excess in the soil or irrigation water, boron-tolerant crops may grow satisfactorily whereas sensitive crops may fail.

The evaluation of water quality and plant tolerance of salts and boron are discussed in detail in Chapter 3. Relative salt tolerance of agricultural and landscape species is shown in Tables 3-6 (p. 3-18) and 3-7 (p. 3-21). Salt tolerance of some of the more important turfgrass species is shown in Table 6-1. Relative boron tolerance of crops and landscape species is presented in Table 3-8 (p. 3-22). Management of saline soils and water is covered in Chapter 7, and additional information on the movement of boron in soil is included in Chapter 13.

Management Requirements

Crop selection is influenced by the availability of management skills and the kind of operation that the managing agency or leasee is willing and able to provide. Included under management responsibilities are: All decisions regarding variety selection, scheduling of activities, preparation of seedbed, weed and pest control, fertilization, irrigation timing and application, labor management, and marketing of the crop.

Both very coarse and very fine textured soils require greater skill in timing and application of irrigation water when using surface irrigation methods. Some crops, beans for example, are susceptible to disease under excess moisture conditions and therefore are not a good choice for heavy-textured soils, where land is poorly graded or unusually variable in water intake rate, or where management skills are low.

Table 6-1. Salt tolerance of turfgrass [4].

Low tolerance EC_e = less than 4[a]	Moderate tolerance EC_e = 4-10	High tolerance EC_e = 8-15
Kentucky bluegrass	Alta fescue	*Purcinellia distans*
Highland bentgrass	Perennial ryegrass	Common bermuda
		Hybrid Bermuda
		Tiffway Tiffgreen Sunturf
		Seaside bentgrass
		Zoysia
		St. Augustine

a. EC_e = Electrical conductivity of the soil saturation extract expressed as deciSiemens/m or millimhos/cm representative of the more active part of the root zone.

Where the amount (depth) of water to be applied far exceeds the crop requirement (discussed in Chapter 5) or if off-line storage is inadequate, the frequency of irrigations may not allow adequate time for the soil to dry. Cultural operations such as cultivation, pest control, and harvest will compact the soil if it is too wet. An important management skill is the ability to judge whether the soil is dry enough to resist equipment or animal compaction. The inability of management to make such a judgement may dictate the selection of a crop which requires fewer cultural operations.

Nitrogen management of some crops requires skill. Because wastewaters often contain much higher levels of nitrogen than do normal sources, special consideration must be given to the detrimental effects of excessive nitrogen on both the crop and the environment. For example, cotton yields can be reduced and defoliation and subsequent harvest made more difficult by excessive nitrogen applied late in the season. In mixed grass-legume pastures, high nitrogen applications can result in the grass outcompeting the legume, although heavy grazing can mitigate this effect.

Nitrogen and Phosphorus Uptake

Knowledge of nutrient uptake and removal by crops is required (1) in order to adjust the regular fertilization programs to take into account nutrients supplied by the water, and (2) to determine the likelihood that a large amount of nutrients will be transported below the root zone and into the groundwater. In studies where species such as sudangrass, bermudagrass, and reed canarygrass were shown to take up large amounts of nitrogen, it was not because of some differential ability of those species to take up nitrogen, rather it was due to their very high productivity. Therefore, if the objective is to remove nitrogen or some other nutrient from the soil, the selection criterion should be high dry matter productivity and not rate of nutrient uptake. Using this criterion, we find that plants such as a warm season grass (like bermudagrass) can "harvest" large amounts of nitrogen. Because bermudagrass in much of California is dormant during the cold winter months, its nutrient uptake during that period would be rather low or nonexistent. It is possible to increase nutrient uptake of bermudagrass by interseeding a cool season annual, such as ryegrass, into the bermudagrass sward. This might provide for the uptake of more nitrogen during the cooler half of the year. The interseeding of ryegrass or a winter cereal into intensively managed bermudagrass pastures in southern California is a popular practice. Removal of nitrogen in relation to yield for various crops is listed in Table 12-2 (page 12-8).

Maximizing Consumptive Use of Water

The objective of this book is to encourage the most beneficial use of reclaimed wastewater for irrigation. Where land area or management skills are severely limited, it may be possible to produce a crop even though a liquid loading rate will be used which exceeds the crop irrigation requirement. This can properly be termed "disposal" or "land treatment" rather than irrigation. Water use by plants is related primarily to climatic factors and to the length of time when a full plant canopy is present. In addition, there are some differences in water use between categories of plants, and these are discussed in detail in Chapter 5. Some crops, notably cool season forages and coniferous trees, go through a period of slow growth during the warmest months, thus reducing water use somewhat. Chapter 5 also includes maps of California which depict normal reference evapotranspiration values for each month and for a year.

Rice is sometimes misperceived as a highly consumptive crop. In fact, much of the water used in rice culture passes through the field and is not actually consumed. Irrigation of rice with treated wastewater is discussed later in this chapter.

Economic Considerations

The relative ability of a crop to produce a profit is determined by several factors and is dependent on local market conditions. This is a complex subject and is beyond the scope of this discussion. Where water or site characteristics are limiting or where the objective of an irrigation project includes disposal, the economic value of the crop may not be the most important factor in crop selection. In recent years in California, the acreage of sorghum, oats and several forage crops has decreased because of low prices. Also some forages which have desirable cultural characteristics have low feeding digestibility or palatability. Farmers usually do not have enough financial incentive to grow such crops.

Profitability of crop production is strongly influenced by the yield which can be obtained. Cooperative Extension county offices have calculated "break-even" yield for some crops based on costs of production in the local area. If some characteristic of the treated wastewater or the way in which it is supplied results in lower yields, the farmer may not be able to achieve the break-even point. This may be offset by the value of the water and the nutrients it contains (see Chapter 9).

Climate Requirements

Considering climate alone, farmers in many parts of the Pacific Coast and southwest U.S. are blessed with a wide range of crop choices. At the same time, large variations in climate over short distances make it difficult to provide guidelines for any specific location, especially in foothills, coastal areas, and mountain valleys. Crops differ in their requirements for heat, chilling and freezing, frost-free period, day length, and relative humidity.

Climatic conditions have a significant influence on forage crop selection. Many forage crops and turfgrasses can be classified as perennial cool season plants. These plants include bluegrass, bromegrasses, fescues, ryegrasses, orchardgrass, reed canarygrass, wheatgrass, timothy, clover, trefoils and many others. These species evolved under temperate conditions and therefore can tolerate cool weather as well as various degrees of freezing weather. They are less tolerant of hot weather but frequently do well with adequate summer irrigation. During the hottest months, even under adequate irrigation these plants may experience a stagnant growth period or "summer slump".

Warm season perennials, including bermudagrass, St. Augustine-grass, dallisgrass, and rhodesgrass, are tropical in origin and thrive in climates with hot summers and mild winters if adequate water is supplied.

Winter annuals such as the winter cereals are grown throughout the state. Some can stand winter cold and snow while others must be planted in the spring under warming conditions. Plant pathogens such as barley yellow dwarf virus are problems in winter cereals under humid conditions.

Summer annuals such as corn, sudangrass, and sorghum grow only from late spring to mid fall. They are tolerant to hot summer temperatures when irrigation is adequate but are intolerant of freezing. Corn and sorghum also yield less in areas where summer marine fogs are prevalent. Cotton requires approximately 2500 degree days or heat units (base 60°F, triangulation method) and can be severely set back by night temperatures of less than 60°F (15.6°C). This temperature requirement limits commercial cotton production in California to Merced County (approximately 37°N) and south, although there is some interest in cotton production in the northern Sacramento Valley. Rice will not grow well if the night temperature is below 55°F (12.8°C) during the period 7 to 14 days before flowering, nor will it produce well if the irrigation water in the field is below 80°F (26.7°C).

Soil Physical Characteristics

Soil texture does not directly influence the selection of crops which are irrigated with treated wastewater. However, a combination of soil texture and soil structure, in particular the presence of restricting layers, can be an important selection criterion. Ease of tillage under wet soil conditions and irrigation is affected by soil physical characteristics.

Poor soil aeration is the consequence of flooding and soil compaction. There are wide variations in tolerance to poor aeration depending on duration, stage of development, and species. Dormant trees can survive many weeks of flooding in winter with little or no permanent injury, but a single day of flooding during the growing season may seriously injure some species, e.g, peaches and walnuts. Grass species vary widely in tolerance to flooding and are more tolerant when dormant than when growing [5]. Flooding on a sunny day is more injurious than flooding on a cloudy day. Symptoms include wilting, yellowing of leaves, reduction in growth, and eventual death of most plants if the soil in which they are growing is saturated. These symptoms are usually attributed to reduced absorption of water caused by injury and death of the roots. Susceptibility of roots to attack by fungi and other organisms is often increased by poor aeration of the roots. A number of pathogenic species of organisms grow well in poorly aerated soils, and this combined with reduced root growth results in injury to root systems of citrus, avocado, pine and other species. Because tailwater from wastewater-irrigated fields must (in California) legally be contained on the property, one may want to select a crop which can tolerate temporarily flooded or saturated soil conditions as can occur at the bottom end of a field. However, a properly designed tailwater return system will eliminate this problem. Leguminous forage crops (clovers, alfalfa, vetch) are generally less tolerant of standing water than grasses. Among the legumes, strawberry and ladino clovers are more tolerant than alfalfa.

Tolerance of Soil Acidity

The areas with strongly acid soils (pH < 5.5) in California and the arid and semi arid southwest U.S. are relatively small. They are mainly confined to upland areas with annual precipitation greater than 25 inches (65 cm), recently oxidized marine sediments, and poorly buffered soils with a long history of the use of acidifying fertilizers. It is possible to select plant species which are relatively tolerant of low pH. However, in most cases it is more practical to correct low pH with applications of liming materials and to provide an adequate fertilizer program. Practical guidelines are provided in the Western Fertilizer Handbook [6].

SELECTION OF CROPS FOR SPECIAL SITUATIONS

The crops most often irrigated with reclaimed wastewater in California are forages, turfgrass, cotton, corn and sorghum, winter cereals, and woody perennial landscaping [7]. Besides these species, a wide variety of other crops are produced with wastewater. We comment briefly on rice, woody perennials for biomass, forages, and turfgrass because these crops have special characteristics which may lend themselves well to wastewater irrigation.

Rice

Rice is an appropriate crop for irrigation with treated wastewater and can be grown where soils are too impermeable for any other crop. For this reason, it can be grown as a "reclamation crop", that is, grown on slowly permeable sodic (alkali) soils while they are being reclaimed with amendments. After several years of proper treatment, the soil structure may be improved enough to permit the production of other crop species (see Chapter 7). At the present time, the irrigation of rice with treated wastewater is controversial in California. As of 1980, it was practiced in six locations in California [8]. There is some concern that nutrients in wastewater will nourish algae in the floodwaters, reducing activity of fish that prey on mosquito larvae. Mosquito-borne diseases (e.g., encephalitis) are a serious concern in California, and any activity which results in slow moving water has been a concern of health agencies. As of this writing, at least one Regional Water Quality Control Board in California will not permit irrigation of rice with reclaimed wastewater.

Woody Perennials for Biomass

Eucalyptus and poplar plantations irrigated with wastewater are being studied in California as a potential source of firewood and fuel for biomass-fired power plants (personal communication, R. M. Sachs, University of California, Davis). The intention is to use marginal land and treated wastewater for these fast-growing species. Trees are harvested at 2- to 4-year intervals, leaving stumps which resprout.

Forage Crops

Forages used successfully in wastewater irrigation include reed canarygrass *(Phalaris arundinacea)*, bromegrass *(Bromus spp.)*, tall fescue *(Festuca arundinacea)*, perennial ryegrass *(Lolium perenne)*, and coastal bermudagrass *(Cynodon dactylon)*. These grasses have high nitrogen requirements, are somewhat tolerant of poor drainage or flooding, and are relatively tolerant of high salinity and boron in wastewater. Field observations of experienced pasture managers indicate that reed canarygrass, tall fescue, and bermudagrass are more tolerant to flooding than some of the other pasture grasses. Field crops that are most popular include barley, sorghum, corn, and milo. Tolerance of poor drainage by these crops may be somewhat less than for the forages. The salinity tolerance of several forages and field crops is discussed in Chapter 3. Among the forage crops that are frequently used in irrigated pastures, bermudagrass and birdsfoot trefoil are most salt tolerant, followed by tall fescue, reed canarygrass, strawberry clover, perennial ryegrass, and orchardgrass. White clover, red clover, and alsike clover are the least tolerant species that are frequently used in irrigated pastures in California. Although barley has some demonstrated tolerance to salinity, the more popular annual forages such as oats and corn are less tolerant to saline soils and irrigation water.

The natural habitat of reed canarygrass is poorly drained and wet areas. It is also more drought tolerant than many cool season grasses grown in the humid and subhumid regions. However, it tends to "winter kill" on dry upland soils if snow cover is sparse and temperatures are well below freezing. Reed canarygrass is very tolerant of flooding. The following range (in days) for tolerance to spring flooding has been reported: mature plants, 49 or more; seedlings, 35 to 49; seed, 35 to 56. No damaging effects were found when this species was grown in pots with one inch (2.5 cm) of water over the soil surface for three months [9]. Reed canarygrass is not adapted to saline conditions but tolerates a pH range of 4.9 to 8.2.

Reed canarygrass is as digestible to ruminants as most of the perennial temperate grasses and legumes, and is more digestible than some. Many workers have reported that the digestibility of reed canarygrass is equal to or higher than that of alfalfa. Lack of palatability (apparently related to the presence of alkaloids in the plant material) is the most frequently cited reason why this species has not become a leading forage grass in its area of adaptation. Poor performance of lambs and ewes, as well as cattle, have been demonstrated in a variety of studies; this poor performance is attributed to the low palatability of the forage.

Reed canarygrass has not been a popular pasture grass in California but is used in wet meadows and irrigated pastures at upland altitudes. Establishment of reed canarygrass from seed is often difficult; vegetative propagation is more successful.

Tall fescue is another cool season grass that appears to have some tolerance to flooding. Observations of irrigated pastures show that the poorly drained areas typically are populated by tall fescue only, even though the original seed mix may have included other grasses such as orchardgrass and perennial ryegrass. This implies that orchardgrass and perennial ryegrass are not as tolerant to these poorly drained areas as tall fescue.

Tall fescue has been a popular grass in irrigated pasture mixes for many years. Although it is less preferred by livestock than orchargrass or perennial ryegrass, it is quite productive. Tall fescue is tolerant of poor drainage, particularly in the winter. It is found growing in damp pastures and wet places throughout the world. It is one of the best grasses available for poorly drained soils, and it is extensively used as a grass constituent of seed mixtures for irrigated pastures throughout the western U.S. Its ability to grow on wet soils, to tolerate both alkalinity and salinity, and to produce a heavy turf makes it an excellent grass for such sites. Although tall fescue grows well on wet or dry soils, it uses essentially the same amount of moisture during the growing season as alfalfa and bermudagrass.

Although tall fescue has many valuable attributes as a pasture grass, cattle grazing pure stands occasionally experience nutritional problems. As with reed canarygrass, the presence of a group of alkaloids influences the palatability of this species. A seed-borne fungus has recently been implicated in this poor livestock performance.

Bermudagrass will tolerate flooding for long periods but produces little if any growth on waterlogged soils. Bermudagrass has been observed growing around stock water ponds in the foothills of California. As stock water ponds recede during the summer the bermudagrass stolons follow the receding water line and actually grow out into the pond.

Bermudagrass is a warm-season grass which actively grows during the warm spring, summer, and early fall months. During the cool winter months bermudagrass is dormant and under severe cold will be winter-killed.

Bermudagrass is frequently considered to be a weed and therefore seldom meets acceptance or even consideration as a forage grass, especially in more temperate regions of the U.S. and California. However, the availability of high quality forage varieties has made bermudagrass a highly desirable forage species in warm areas. Bermudagrass is a popular summer forage in desert locations of southern California. Some forage varieties of bermudagrass have sufficient cold tolerance to survive in pastures throughout the Central Valley of California.

Turfgrasses and Other Landscape Species

Californians have been irrigating farmland with wastewater for many years. In recent years the trend has been to reuse wastewater for landscape irrigation and recreational impoundments [10]. Landscaping still accounts for a small percentage of the total area irrigated with reclaimed wastewater (see Table 1-2, p. 1-4), but the potential growth for use on landscaping is large. By far the greatest growth in wastewater reuse is projected to occur in the Los Angeles, Santa Ana, and San Diego areas [11]. Some of the factors contributing to this potential growth are high fresh water prices ($250/acre-ft and higher), a large area of landscaping compared to the area of agricultural land, and the possibility of selecting ornamental species that will tolerate poor water quality. Regarding the last point, aesthetic appearance rather than yield is usually the most important criterion for ornamentals. Thus, levels of salt in the water which result in a growth decrease but do not harm the appearance of landscaping can be tolerated.

Currently treated wastewater is being used to successfully irrigate turfgrass and other types of landscaping in California. A 1981 survey of California golf courses showed that 61 out of 819 have been irrigated at least in part with reclaimed wastewater [12]. In only one case has the use of reclaimed wastewater been abandoned. In this case management was already marginal due to existing problems of poor drainage and salinity.

An example of wastewater reuse for irrigation of landscaping in California is, in Pomona, in the eastern part of Los Angeles County.

Water from the Pomona Water Reclamation Plant is currently going to nine users. Six of these users, representing 700 to 800 irrigable acres and about 1350 acre-ft/yr of reclaimed water are irrigating landscaping. One user, California State Polytechnic University, irrigates about 450 acres of landscaping, both shrubs and turfgrass. Twelve acres of this is irrigated with buried drip lines and half of that has been operating successfully since 1977. Additional details on Pomona wastewater reuse are provided in Appendix A.

MANAGEMENT OF FORAGE CROPS

Perennial forage crops require less management than most crops. The grass can be grazed or cut and sold as hay. Field crops are usually annuals and therefore require more management (planting, cultivating, havesting, and field preparation). Combinations of crops in sequence such as corn (in the summer) followed by barley, oats, wheat, or ryegrass (in the winter), can increase productivity and nutrient removal. Management techniques such as minimum tillage farming reduce the labor involved and also reduce the potential for soil erosion. The management of cereals for forage crops does not differ greatly from their management as grain crops.

To carry out a successful irrigated pasture operation using wastewater irrigation requires extensive planning. Successful pasture establishment requires planning to meet the proper planting date. Pasture management requires the careful coordination of the irrigation system and the harvesting system (mechanical or grazing animal).

Before the crop is established, the most suitable irrigation delivery system must be selected and installed. Where surface irrigation is to be used on a pasture the land must be levelled and graded with a slope of 0.1 to 0.4 ft/100 ft. Land grading will increase irrigation efficiency and reduce weed and mosquito problems caused by poorly drained low spots. The use of a sprinkler irrigation system can reduce the requirement for level land to some extent. However, sprinklers can be difficult to manage in areas of strong winds. Irrigation system design is discussed in some detail in Chapter 8.

Weed control before seeding is a major consideration. Land grading will reduce low spots where weeds tend to become established. In commercial operations where the land has not been farmed, or in irrigated pasture, weeds are commonly reduced by growing a hay crop or grain crop prior to seeding the pasture. Weed control can also be accomplished by irrigating weeds up and discing them under early in seedbed preparation. Once land preparation for the irrigation and drainage system is completed and weeds are reduced, a seedbed can be prepared. If fertilizer is to be applied, incorporate it near the end of seedbed preparation just prior to planting. Seed can be planted with a seed drill or by broadcasting, taking care not to place the seed more than 1/4 inch (0.6 cm) deep.

Fall seedings can be established with little or no irrigation if winter rains come regularly, and hot spells are not a problem. It is safest, however, to have the irrigation system ready to go at seeding time in case rains are insufficient. Spring plantings of irrigated pasture are generally not recommended because it is difficult to establish plants during the spring and summer, and the pasture would not be usable during the first growing season.

Irrigated pasture management requires coordination of the irrigation and harvesting system. Whether pastures are grazed or harvested mechanically, they should not be muddy during harvest. Therefore, part of the pasture should not be irrigated for several days prior to grazing or harvesting. If the pastures are to be grazed, this requires a pasture rotation system that coordinates the irrigation with the rotation of the livestock. A pasture can be subdivided into as many segments as necessary to facilitate animal and irrigation rotation. A simple six-pasture rotation might use the following sequence: Pasture A would be allowed to dry for seven days prior to a seven-day period of grazing. Pasture B would be past its seven-day drying period and would be grazed while Pastures C, D, E, and F would be irrigated. One week later the sequence would be moved up with Pasture F allowed to dry while Pasture A was being grazed and Pastures B, C, D, and E were being irrigated. This sequence would take 42 days to make a full circle and allow 35 days of rest from grazing following grazing.

On coarse-textured soils where the drying time before grazing would only require three or four days, the rotation schedule could be altered to an eight pasture system where the irrigation system and the animals are moved every three or four days, making the complete cycle every 24 to 32 days.

The irrigation system should be designed so that each pasture can be irrigated separately. When planning the rotation system, allow approximately 30 days for the plants to recover between grazing. Thirty days of rest is adequate for most irrigated pasture species to recover from previous grazing.

Attention should be paid to the carrying capacity of the pastures so that overgrazing will not occur. A good irrigated pasture should support one to two animal units per acre from March through September. Table 6-2 provides animal unit conversions for various kinds and ages of livestock. For example, a 1,000 lb cow or steer, or five mature sheep weighing about 120 lb each, would constitute about one animal unit. Immature animals will be gaining weight so their animal unit value will increase throughout the season. One acre of pasture should feed two 500-700 lb steers during the growing season. These carrying capacity guidelines can be adjusted with experience.

Table 6-2. Animal unit conversions.

Kind and age of stock	Average weight	Animal units per head	Head per animal unit
	lb		
Beef cows, steers over 2	1000	1.00	1.0
Yearlings 1 to 2, average	627	.75	1.3
Calves 3 months to 1 year	400	.50	2.0
Dairy cows (350# production)	1100	1.25	0.8
Dairy heifers 1 to 2 years	600	.70	1.4
Dairy calves 3 months to 1 year	300	.40	2.5
Sows[a]	350	.50	2.0
Pigs after weaning[a]	70	.25	4.0
Pigs fattening[a]	150	.40	2.5
Ewes and mature sheep	120	.20	5.0
Lambs under year	70	.16	6.0
Horses, light work	1200	1.00	1.0

a. Swine are shown in full animal unit equivalents although they would not get all the feed required from pasture. A sow can get up to 50% so would be figured at half the .50 shown, or at .25, if getting half of the feed from pasture.

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CHAPTER 7

WATER MANAGEMENT FOR SALINITY AND SODICITY CONTROL

J. D. Oster and J. D. Rhoades

INTRODUCTION

When municipal wastewaters are used for irrigation, water management for salinity and sodicity (sodium) control will be similar to that used for fresh water sources. All irrigation waters contain salts; however, wastewaters contain more salts (200-500 mg/L) than are present in the municipal water supply. The proportion of sodium in relation to other dissolved cations is also increased.

The primary concerns in water management for salinity and sodicity control are:

1. Proper selection of crops: adequate salt and specific ion tolerance of the crops grown
2. Proper seed-bed management: satisfactory levels of salinity, sodicity, and specific ion concentrations in the soil seed bed during germination
3. Adequate irrigation for both crop growth and leaching
4. Sufficient drainage to dispose of the leaching water.

Crop salt tolerance as related to water-quality evaluation is covered in greater detail in Chapter 3.

HOW SALT AFFECTS PLANTS

Three salt effects on plant growth are (1) osmotic, which results from the total dissolved salt concentration in the soil water, (2) specific ion toxicity, which results from the concentration of an individual ion, and (3) poor soil physical conditions, resulting from high sodium and low salinity.

Osmotic Effects

With increasing soil salinity in the root zone, the plant expends more of its available energy on adjusting the salt concentration within its tissue (osmotic adjustment) to obtain the water it needs from the soil. Less energy is available for plant growth. Excessive salinity generally causes stunting of plants. Above a threshold level (Fig. 3-1, page 3-20), the higher the salinity, the greater the effect [1]. Reduced growth may not always be undesirable, provided the plant remains healthy. Salinity stress on cotton, for example, reduces vegetative growth before it reduces lint yield.

Climate (temperature, humidity, smog) can modify plant response to salinity [1,2]. Salt injury is often more severe under hot, dry conditions, especially in sensitive crops. The onset of hot weather can cause the sudden appearance of leaf burn in woody species. Reduced tolerance has been reported for alfalfa, clover, bean, beet, cotton, squash, and tomato. Salt accumulates in the soil faster during hot weather because of more frequent irrigation and greater plant water usage. The problem is more severe if irrigation is inadequate. Underirrigation can result from inadequate irrigation capacity, inadequate soil infiltration, or both. Plants grown under saline conditions are more resistant to ozone (smog) damage [3]. Also, leafy vegetables and forage crops may appear more salt-tolerant in areas with air pollution than elsewhere.

Specific Ion Toxicity

If growth depression is due to excessive concentrations of specific ions, rather than to osmotic effects alone, it is called "specific ion toxicity."

Boron

Boron can become toxic at levels only slightly greater than required for good plant growth. Symptoms of excess boron include leaf tip and marginal burn, leaf cupping, chlorosis (yellowing leaves), anthocyanin (blue and red leaves), rosette spotting, premature leaf drop, branch dieback, and reduced growth.

Chloride

Chloride can cause specific injury (leaf burn, chlorosis, twig dieback) to woody plant species (stone fruits, citrus, and avocados), but it is not a toxic ion for vegetable, grain, forage, or fiber crops. Tolerances vary among woody species and even among varieties or rootstocks within a species. These differences usually reflect the plant's ability to exclude or retard chloride accumulation.

Bicarbonate

Bicarbonate indirectly affects iron nutrition and sodicity through its effect on soil pH and lime precipitation. Iron availability decreases with increasing pH in part because of iron adsorption on lime and also because of the precipitation of iron carbonates and reduced solubility of iron oxides. Lime precipitation reduces the soluble calcium concentration, which in turn increases the relative amount of soluble and exchangeable sodium.

Sodium

The effect of sodium can be both direct (plant accumulation) or indirect (nutritional imbalance and impairment of soil physical conditions). Direct effects (leaf burn, chlorosis, twig dieback) can occur in avocado, citrus, and stone fruit trees. Nutritional imbalance is a consequence of insufficient concentrations (<1 mmol/L) of calcium or magnesium to prevent uptake and accumulation of sodium [4]. Consequently, as sodium levels (in a nonsaline soil) increase, the likelihood for nutritional problems increases. When the soil becomes increasingly saline, nutritional effects induced by high sodium decrease and osmotic effects begin to predominate.

Poor Soil Physical Conditions

Another indirect effect of high sodium content is poor soil physical conditions (crusts, water-logging, poor permeability). Almost all crops (except rice) can be adversely affected. Exchangeable sodium enhances clay swelling and dispersion (disaggregation), which decreases soil permeability to water and air. Clay swelling and dispersion depend on the levels of exchangeable sodium and salinity of the irrigation water and soil solution.

HOW SALINITY AND SODICITY ARE MEASURED

Water

Salinity of an irrigation water is determined by measuring its electrical conductivity and the concentration of boron, chloride, bicarbonate, sodium, calcium, and magnesium. This information is essential for the evaluation of potential problems in regard to osmotic, specific ion, and sodicity hazards. If the irrigation water composition varies during the growing season, samples must be taken and analyzed periodically to assure adequate characterization. Sample collection is discussed in Chapter 3.

The electrical conductivity of a water is a quick measure (~5 min/sample) of its total dissolved salt concentration. The electrical conductivity of a water increases with increasing salt content. It was commonly expressed as mmho/cm. The equivalent SI metric unit is decisiemens per meter (dS/m): one dS/m equals one mmho/cm. Currently both units are used; the use of dS/m is increasing.

Values for salinity are also reported as total dissolved solids (TDS) in units of ppm, mg/L, or mg/kg of water. For most agricultural purposes, these can be considered numerically equivalent. The values for electrical conductivity (EC) and TDS are interchangeable within an accuracy of about ±10%. The equations used to convert EC to TDS (or vice versa) are:

$$\text{EC (dS/m)} \times 640 = \text{TDS (mg/L)} \qquad [7\text{-}1]$$

$$\text{TDS (mg/L)} \times 0.00156 = \text{EC (dS/m)} \qquad [7\text{-}2]$$

The concentration of sodium in water relative to calcium and magnesium is expressed as the sodium adsorption ratio (R_{Na} or SAR) and is calculated as follows:

$$R_{Na} \text{ or SAR} = \frac{C_{Na}}{\sqrt{(C_{Ca} + C_{Mg})/2}} \qquad [7\text{-}3]$$

where ion concentrations, C_i, are expressed in meq/L.

Chemical laboratory reports often include two sodium adsorption ratios:

1. One is calculated from the ionic composition of the water and labeled as R_{Na} or SAR

2. The other is adjusted for the tendency of calcium precipitation or dissolution. This adjusted sodium adsorption ratio [5] is labeled as adjusted R_{Na}. A procedure for calculating the adjusted R_{Na} is described in Table 3-2 in Chapter 3.

Soil

Soil water extracts are usually obtained in a laboratory from soil samples collected in the field. Ideally, soil samples taken to diagnose potential soil water salinity problems in cropped fields should be representative of the root zone. Since salinity tends to vary considerably from place to place at any depth in the root zone, composite samples from 10 or more locations should be taken for each depth. If there are areas of good and poor crop growth, separate composite samples should be taken from each area. Similarly, if there are different topographic features (i.e., hillsides vs. valleys; furrows vs. beds), or wet and dry areas (trickle-irrigated crops), each should be sampled separately.

The standard procedure is to prepare a saturation extract. Distilled water is added to a soil sample until it is saturated; the surface of the resulting paste glistens, and the paste flows slowly when tipped on its side. The resulting solution, referred to as the saturation extract, is then extracted by vacuum from the sample and its EC is measured. This is sometimes referred to as EC_e, where the subscript e refers to saturation extract. Na^+, Mg^{2+}, Cl^-, HCO_3^-, Ca^{2+}, and B concentrations in the extract are also determined.

Electrical conductivities of the soil water can be measured by other methods [6]:

1. On soil water samples, collected in place with vacuum extractors
2. In soil, using buried salinity sensors
3. In soil, using 4-probe soil-resistivity techniques
4. Remotely, by electromagnetic induction.

Methods 3 and 4 are ideally suited for rapid reconnaissance [7]. Commercial equipment for methods 3 and 4 are available, and the techniques involved are well documented. Commercial equipment is also available for methods 1 and 2; however, these methods are commonly used in research studies to monitor soil salinity at one location for long periods of time.

WATER MANAGEMENT FOR SALT CONTROL

Water management requires an understanding of the following: (1) how soil salinity can increase as a result of irrigation, (2) how soil salinity affects crop growth and yield, and (3) how to estimate crop water requirements, including a sufficient excess of irrigation water for leaching to control soil salinity. This water management section begins with a brief explanation of how salts in the irrigation water influence soil salinity. This is followed by an explanation of how crop yield is affected by soil salinity. The last subsection describes a method to determine the minimum leaching requirement and associated crop water requirement for specific crops and irrigation water salinities.

Basic Aspects

Soil Salinity

Salts are added to the soil in the irrigation water. For example, an acre-foot (1233 m^3) of relatively low salinity irrigation water with an EC of 0.5 dS/m (~320 mg/L) contains 0.43 tons (390 kg) of salt. When water is taken up by plants or evaporates from the soil surface, most of the salt is left behind in the soil. Salt contents of 3 to 4% have been reported [8] for alfalfa grown under saline conditions. At 4%, an annual alfalfa yield of 10 tons/acre (22 Mg/ha) would remove about 0.4 tons/acre (0.9 Mg/ha) of salt. If five acre-ft (1500 mm) of water with an EC of 0.5 dS/m were used to grow the crop, the salt applied per acre would be 2.2 tons (4.9 Mg/ha). Salt uptake by the crop would be less than 20% of that applied. Consequently, repeated irrigation without moving the salts to depths below the root zone (leaching) results in salt accumulation in the root zone. The saltier the water, the faster the accumulation.

If more water is applied than the plant uses, the excess water will leach salts below the root zone. Consequently, the soil salinity will stabilize at some more or less constant value, a steady state, dependent on leaching fraction (the fraction of infiltrated water that passes through the root zone as drainage water). This is illustrated in Fig. 7-1 for two waters of different salinities (1 and 2 dS/m) and a leaching fraction of 0.1. The salinity at the soil surface is the same as that of the irrigation water, whereas at the bottom of the profile it is ten times greater. Plant water uptake consumes nine-tenths of the applied water; the other one-tenth, the leaching fraction, passes through the root zone and contains the salt applied with the water. Consequently, the salinity of the water moving downwards in the lowest part of the root zone is theoretically ten times greater than that of the irrigation water for steady-state conditions. If the leaching fraction were lower than 0.1, the salinity of the drainage water would be higher. If the leaching fraction were zero, soil water salinity in the root zone would continue to increase until its level would be toxic to all plants.

Crop Response

How does crop yield respond to a variable soil salinity with depth like that illustrated in Figure 7-1? Several studies indicated that yield is best correlated to the average salinity in the root zone [9,10]. The average soil solution salinities in Figure 7-1 are 4.3 and 8.6 dS/m. The corresponding ECs of the saturation extracts--upon which the effects of salinity on plant growth have by convention been based--would be 2.2 and 4.4 dS/m. These salinities are 2.2 times greater (a multiplication factor) than the corresponding irrigation-water salinities (1 and 2 dS/m) used to prepare Fig. 7-1. The multiplication factor varies with leaching fraction, as shown in Fig. 7-2 [11].

Leaching Requirement

Irrigation and water movement into and through the soil must be adequate to fulfill both crop water and leaching requirements; drainage must be adequate to dispose of the excess water applied for leaching. The average soil salinity should not exceed the threshold level if yield is not to be affected by salinity. The average root-zone salinity is the product of the irrigation water EC times the

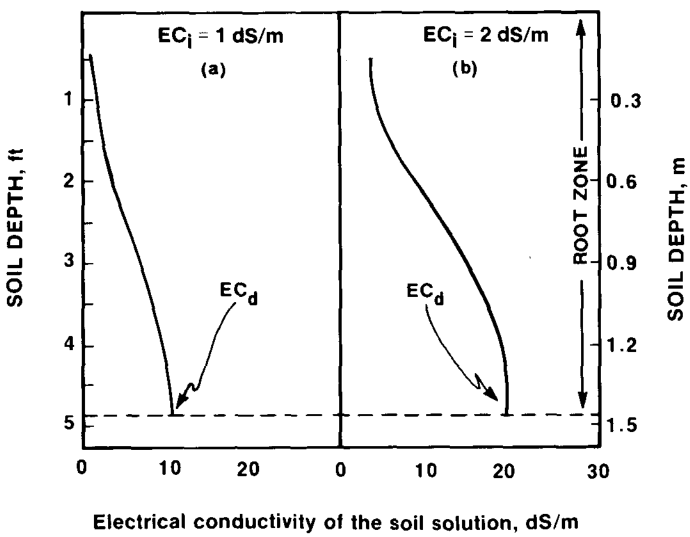

Figure 7-1. The electrical conductivity (EC) of the soil solution through the root zone for two irrigation water (EC=1 and 2 dS/m) and one leaching fraction (=0.1, or 10%).

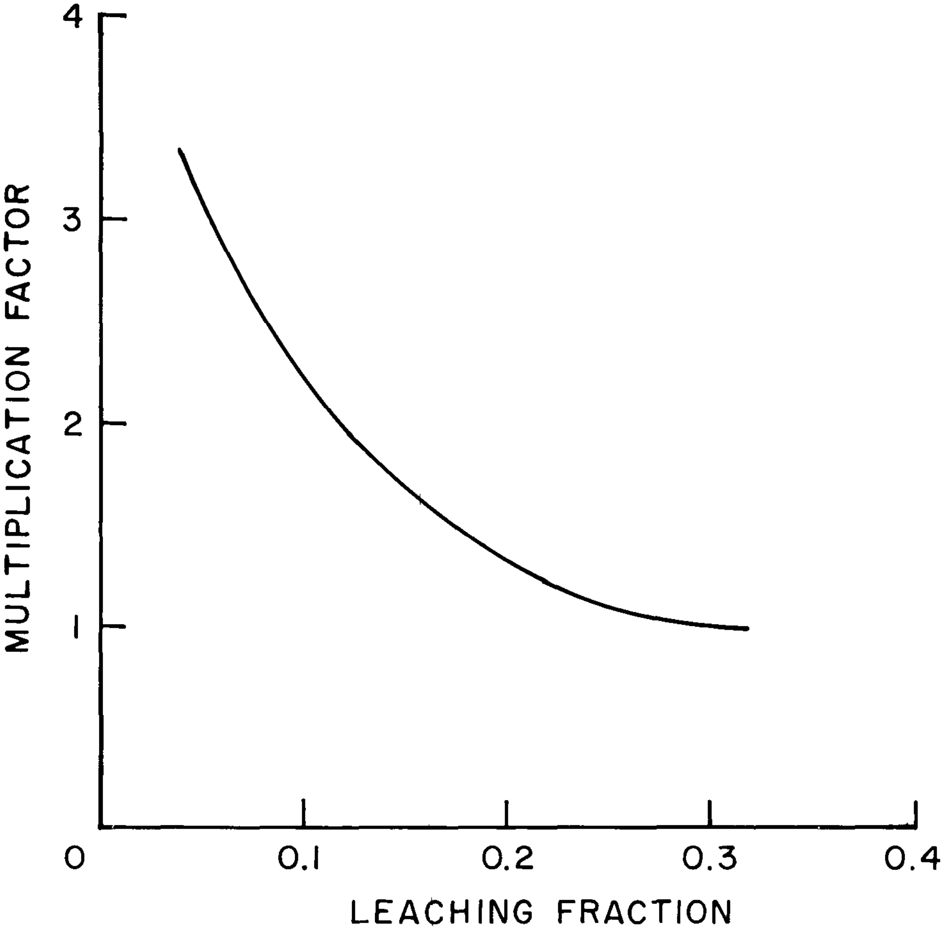

Figure 7-2. Multiplication factor used to interconvert leaching fraction and the ratio of threshold salinity to irrigation water salinity.

multiplication factor from Figure 7-2. For example, given an irrigation water salinity of 2 dS/m and a crop with a threshold salinity of 4 dS/m, the multiplication factor should not exceed 2. According to Fig. 7-2, the required leaching fraction for no yield reduction is between 0.1 and 0.2. Threshold salinity values for plant species may be obtained from Maas and Hoffman [1] and are discussed in Chapter 3.

Figure 7-3 illustrates the use of Fig. 7-2 in a slightly different manner. Figure 7-3 shows how the average soil salinity should change with leaching fraction for two irrigation waters (3 and 1 dS/m). In Figure 7-3, the average soil salinity is the product of the EC of the irrigation water times multiplication factors obtained from Fig. 7-2. The threshold salinities for several crops intersect the curves at different locations. The leaching fraction for each intersection represents a leaching requirement (LR). Both curves and corresponding intersections show that management options for a given water include crop selection and water management to achieve different leaching requirements. The LR can be used to calculate the water requirement with the following equation:

$$\text{water requirement} = \frac{ET}{1 - LR} \qquad [7\text{-}4]$$

where ET represents evapotranspiration, or the amount of water required by the crop.

Some Practical Considerations

The irrigation water requirement, calculated using Equation 7-4, may not be achievable for several reasons. Capacity of the irrigation system, method of water application (sprinkler, trickle, flood), soil permeability, and cultural practices such as tillage and application of herbicides and insecticides often limit irrigation timing and the amount of applied water that infiltrates. Preplant irrigation, a common practice, increases water management alternatives: it reduces soil salinity (especially in the seed zone), fills the soil water reservoir with low-salinity irrigation water, and reduces the amount of leaching required during the growing season.

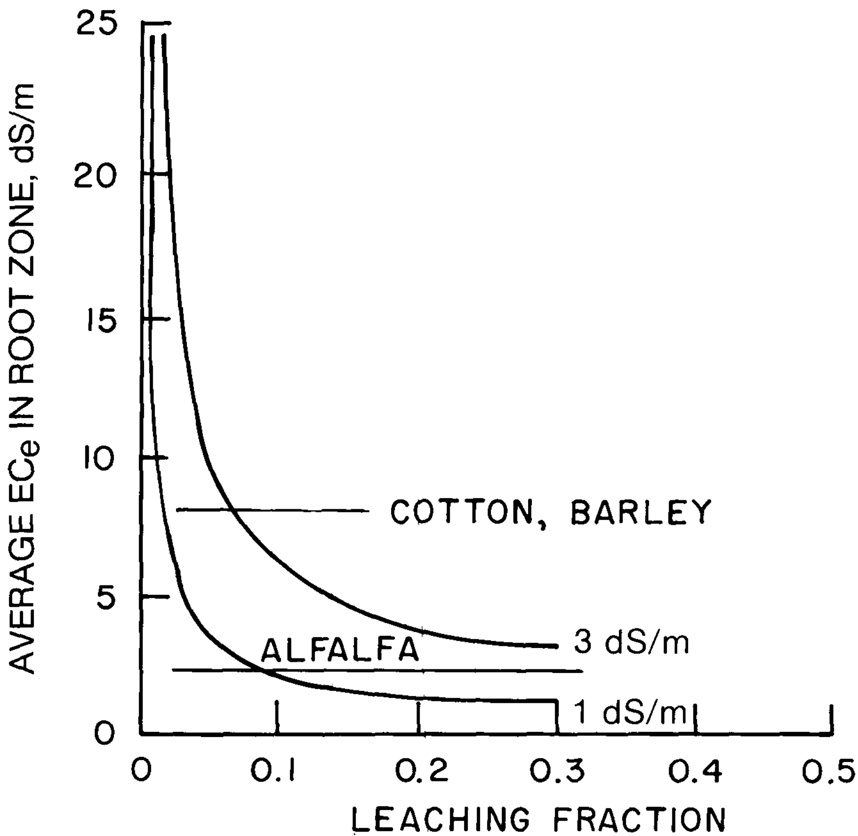

Figure 7-3. Relationship of irrigation water salinity, root zone salinity and leaching fraction.

Sprinkler irrigation can be used to germinate salt-sensitive crops planted into somewhat saline soils (e.g., lettuce in the Imperial Valley), because it uniformly leaches the salt out of the seed zone. Sprinkler irrigation during the daytime can cause salt injury [12]. Leaves wetted by the sprinkling water absorb salts directly through their surface, and injury may exceed that expected from soil salinity. Frequent, light sprinklings should be avoided to prevent any buildup of salt on the leaf surface. When foliage is sprayed, sufficient water should be used to wash excess salts from the leaves. Sprinkler irrigation at night is often the solution.

Trickle irrigation results in a bowl-shaped salinity distribution about the emitter. The maximum zone of soil salinity begins at the soil surface, at the edge of the wetted area, and extends downward and towards the emitter. During a rainstorm or during the rainy season, the water that infiltrates beyond the wetted area of the trickle emitter can "push" the salts into the root zone if it is drier than the soil wetted by rainfall. The drier the root zone, the greater the likelihood for salt damage. This problem can be reduced by irrigating during an individual rainstorm or before the beginning of the rainy season. The higher soil water content in the root zone will reduce the movement of water and salt into the root zone. In San Diego County, the recommended practice is to continue trickle irrigation of avocado until at least 2 inches (5 mm) of rainfall have fallen within a two-week period.

RECLAMATION OF SALINE SOILS WITH TREATED WASTEWATER

In certain cases, a relatively nonsaline wastewater will be used to "reclaim" a saline soil. Soil reclamation generally refers to those farm management practices on an uncropped field that reduce soil salinity to acceptable levels for cropping by leaching or that reduce soil sodicity by application of amendments such as sulfur, sulfuric acid, or gypsum in conjunction with leaching. Electrical conductivities of saturation extracts that exceed 3 dS/m are of concern for moderately tolerant crops; values greater than 10 dS/m would indicate reclamation is needed for almost all crops. The salinity of the upper 2 ft (0.6 m) of soil is of most concern.

Reclamation of the surface 2 ft (0.6 m) of soil is usually accomplished by preirrigation. The application of 4-8 inches (10 to 20 cm) of water before planting, coupled with a similar irrigation immediately following planting, is often sufficient. Preirrigation reclamation can be achieved by flood, sprinkler, or trickle irrigation. Salinity levels higher than 10 dS/m may require more reclamation than can be accomplished by preirrigation.

Saline soils are normally reclaimed by continuous ponding, intermittent ponding, or sprinkling. Fields should be leveled before reclamation begins if water is to be applied by ponding techniques. The greater the depth of water applied, the deeper the soil is reclaimed. Reclamation with intermittent ponding or sprinkling techniques uses from 20 to 50% less water than continuous ponding. Figure 7-4 shows results obtained during the reclamation by intermittent ponding of clay loam and sandy loam soils [13]. The following question and answer illustrates how to use the figure: How much water is required to reduce the salinity from 10 to 2 dS/m in the upper 2 ft (0.6 m) of soil? The desired fraction of original salt to remain after reclamation is finished is 0.2 (the horizontal broken line in Figure 7-4). The corresponding depth of water required per unit depth of soil is 0.6 (the vertical broken line). Since the depth of soil to be reclaimed is 2 ft (0.6 m), the depth of water required is 2 ft x 0.6, or 1.2 ft (0.36 m). This amount of water must infiltrate the soil to achieve the desired reclamation. It should be applied in three or four irrigations, and sufficient time should be allowed between each irrigation for all the ponded water to infiltrate.

Drip irrigation could be used for reclamation, but the zone reclaimed would be restricted to the volume wetted. The resulting reclaimed zone would be bowl-shaped, with the emitter located at the upper center of the bowl. Much of the leached salt would be located at the outermost fringe of the wetted area, and unwetted areas between the emitters would not be reclaimed.

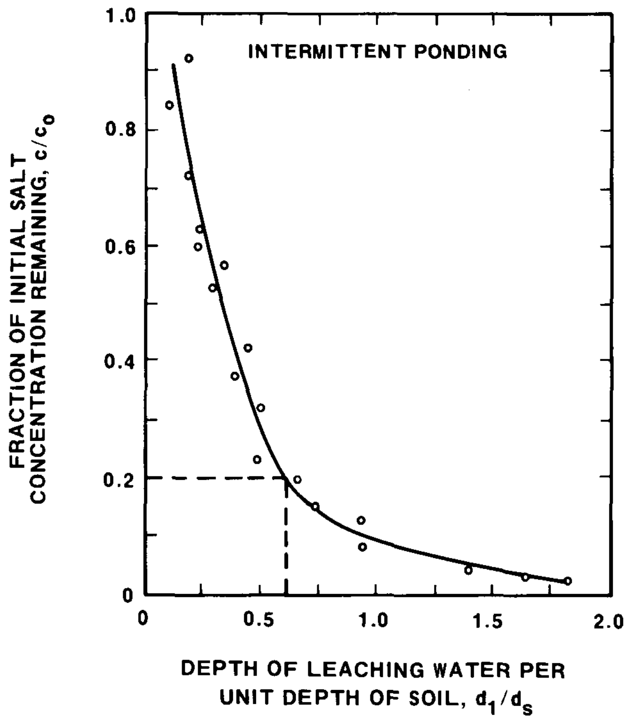

Figure 7-4. Depth of leaching water (d_l) per unit depth of soil (d_s) required to reclaim a saline soil by ponding water intermittently.

IRRIGATION WITH HIGH-SODIUM/LOW-SALINITY WATERS

As previously stated, irrigation with water relatively high in sodium and low in total salt content may result in poor soil physical conditions. The line in Figure 7-5 represents a generalized boundary between stable and unstable soil physical conditions for either the irrigation water or the soil solution [11]. Combinations of salinity and R_{Na} (or adjusted R_{Na}) values that lie above the line are not expected to cause dispersion or clay swelling. Those values that lie below the line can create permeability problems. Figure 7-5 is a graphic representation of criteria presented in Table 3-4, p.3-11.

If either the adjusted or unadjusted R_{Na} and salinity of the irrigation water is close to the boundary given in Figure 7-5, chemical amendments may be required to reduce crusting or increase soil permeability. Gypsum (calcium sulfate) applied to the soil surface or added to the water increases the salinity and reduces the R_{Na} of the water infiltrating into the soil. Both improve the quality of the water in terms of its effect on soil crusting and permeability. The addition of sulfuric acid also has similar effects, since it reacts with soil lime and releases calcium.

With regard to soil permeability below the soil surface, the increased level of salinity due to crop water uptake usually will be sufficient to offset the bad effects of exchangeable sodium. However, if the R_{Na} in the topsoil is greater than 10, then large reductions in permeability can occur if rainfall reduces soil salinity to levels less than 1 dS/m. Chemical amendments such as gypsum, sulfuric acid, and sulfur, in combination with tillage, may be required to alleviate permeability problems.

Reclamation of sodic soils [14] involves the replacement of exchangeable sodium by calcium. The sodium must be removed by leaching. If a native soil doesn't contain sufficient soluble calcium or gypsum, calcium is added to the soil in the form of a soluble salt, or soil lime is made soluble by adding acid or acid-forming materials. The most common additive is gypsum (calcium sulfate), which is mixed into the soil or the irrigation water. Acid or acid-forming additives include sulfuric acid, iron sulfate, aluminum sulfate, and sulfur.

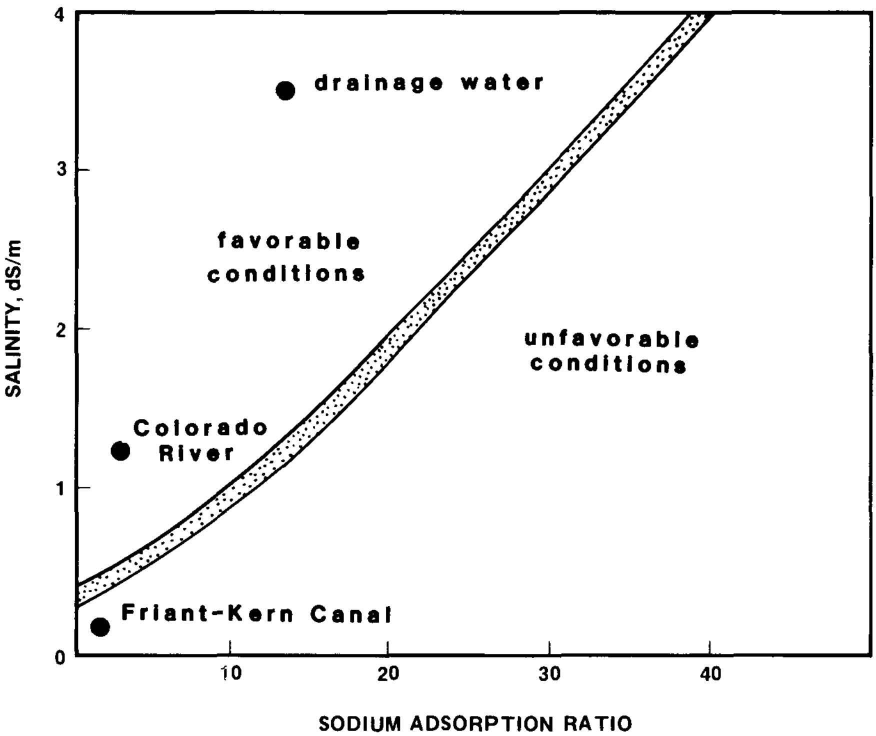

Figure 7-5. Salinity and sodium absorption ratio boundary that divides combinations of both measures into two categories; those which promote good permeability and those which do not. The graph can be used for both irrigation water and soil saturation extract compositions.

Different amendments will reclaim soils at different rates. The ranking with regard to rate is: concentrated sulfuric acid > gypsum > sulfur. The high salt concentration resulting from using sulfuric acid increases the rate at which water flows through the soil [15]. Special equipment is required to handle acid safely. Microbiological oxidization of elemental sulfur, a slow process in cool soils, is required before it is effective in dissolving soil lime.

The amount of gypsum or other amendments added to the soil can be estimated from the amount of exchangeable sodium to be replaced by calcium. It takes one ton of gypsum per acre to replace 1 meq/100 g of exchangeable sodium to a depth of 0.5 ft (0.2 m). The amount of water required to dissolve one ton of gypsum ranges from about 0.25 to 1 acre-ft (300 to 1200 m^3). Reclamation with gypsum may require annual or semiannual application for several years until the soil is reclaimed to a depth of 2 to 3 ft (0.6 to 0.9 m).

SUMMARY

Management options become more limited with increasing salinity, sodicity or concentration of toxic elements and leaching and drainage needs increase. To achieve salinity and sodicity control when using any irrigation water, including municipal wastewater, for irrigation:

* Verify that soil permeability and drainage are adequate.

* Determine initial salinity and sodicity of the soil; reclaim if necessary.

* Determine the chemical composition of the irrigation water: assess potential soil and crop hazards associated with its use.

* Leach to prevent salt accumulation. Do not waste water by leaching more than necessary.

* Healthy plants withstand salinity better. Fertilize; control weeds and insects.

* Local Cooperative Extension or Soil Conservation Service staff are an excellent source of more detailed information necessarily left out of this chapter.

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CHAPTER 8

IRRIGATION SYSTEM DESIGN

R. G. Smith, J. L. Meyer, G. L. Dickey, and B. R. Hanson

INTRODUCTION

Irrigation system design, as presented in this chapter, is divided into three major steps. The first two steps are described in detail because they involve design decisions that are unique to irrigation with reclaimed wastewater. The third step--detailed design of distribution and drainage system components--can be performed following conventional irrigation system design procedures. Figure 8-1 shows a flow chart of the key steps in the irrigation system design procedure and the relationship of these steps to other chapters.

In this manual, production of a marketable crop is considered to be a principal objective of the reclaimed-wastewater system. Procedures in Step 1 design depend on the amount of water applied relative to the water needs of the crop. For design purposes, systems are categorized as Type 1 or Type 2 based on the following definitions.

Type 1--Systems designed to apply just enough water to meet the total irrigation water requirements of the crop, which include crop needs plus allowances for distribution system efficiency (see Equation 8-2).

Type 2--Systems designed to apply water in excess of the total irrigation water requirements of the crop.

In Type 1 systems, land area is not a limiting constraint, and sufficient area is available to allow the wastewater to be applied at normal agricultural irrigation rates. Typically, the land is either owned or leased by the wastewater management entity, or the reclaimed water is sold to area growers under contract with the entity. In Type 2 systems, the land area available is a limiting constraint, so irrigation rates must exceed normal agricultural rates in order for the total available quantity of reclaimed wastewater to be applied. Land area may be limited simply because sufficient land at reasonable conveyance distances from the source of reclaimed wastewater is not

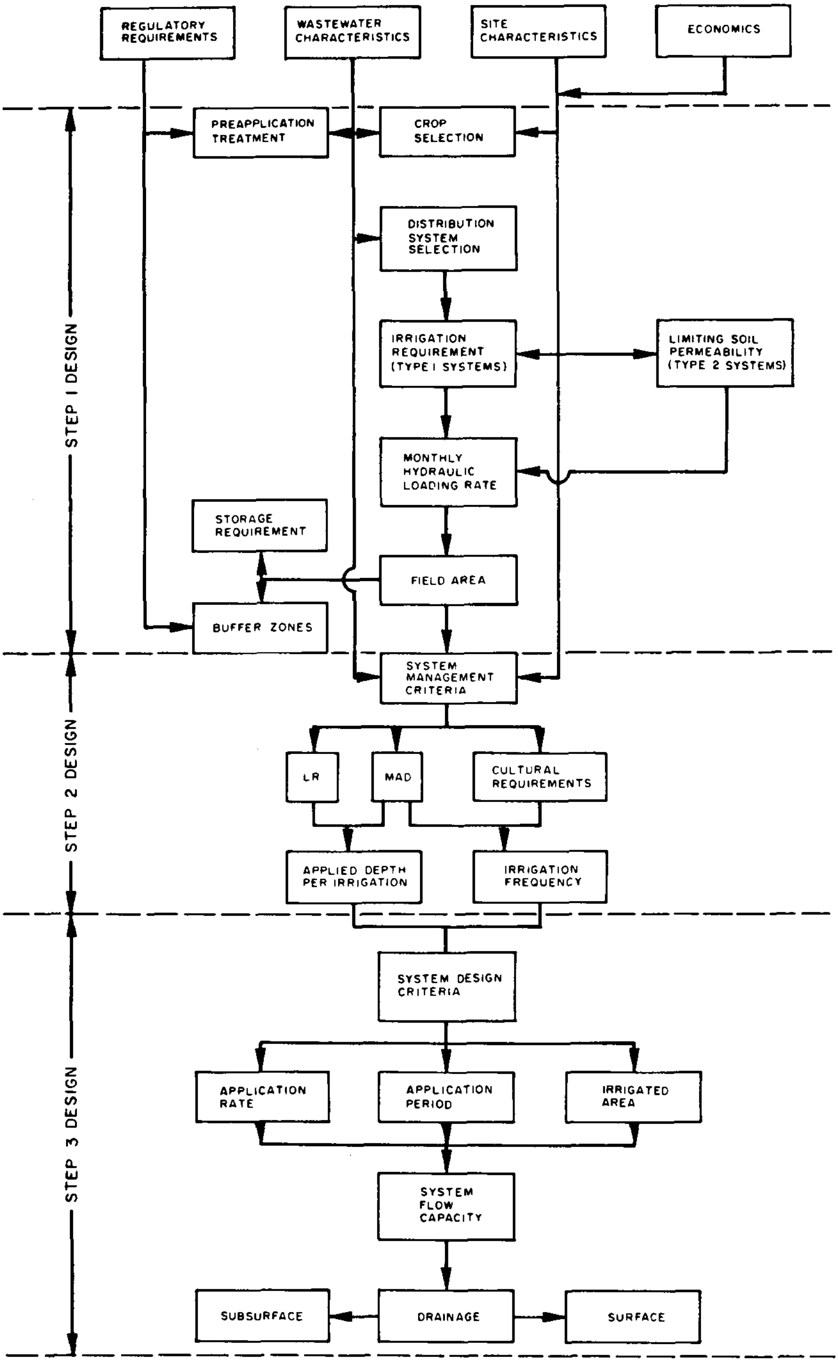

Figure 8-1. Irrigation system design procedure.

available for acquisition by the wastewater management entity or because the cost of available land is sufficiently high so that it is economically advantageous to minimize the land area used for reclaimed wastewater irrigation.

STEP 1 DESIGN--LAND AREA AND STORAGE REQUIREMENTS

The product of the first design step is the total land area and storage volume required for the system. Step 1 design procedures are described separately.

Type 1 Systems

As indicated in Figure 8-1, the intermediate steps in the determination of land area and storage requirements are:

1. Crop selection
2. Distribution system selection
3. Determination of irrigation water requirements (hydraulic loading rates)
4. Determination of field area requirements
5. Determination of storage requirements

Crop Selection

Crop selection is the first step in the design process, because most of the other design decisions (preapplication treatment, distribution system, and hydraulic loading rates) depend on the crop. Crop selection is discussed in Chapter 6.

Distribution System Selection

The type of distribution system is selected at this step of the design, because it is necessary to know the application efficiency of the distribution system to determine the total irrigation requirements.

The factors considered in selecting a distribution system include the following:

1. Site characteristics--topography, soil permeability, soil water-holding capacity (WHC), and soil depth
2. Crop grown

3. Management and skilled labor requirements
4. Cost--capital + operating
5. Water-quality and -quantity requirements

Distribution systems may be classified into three broad categories: sprinkler systems, surface systems, and drip systems. However, drip systems are not often used with reclaimed wastewater, because the water supply must be consistently clean to prevent plugging of emitters. The specific types of sprinkler and surface systems commonly used are listed in Table 8-1 along with salient features of each and conditions suitable for their use.

Costs are not listed in Table 8-1, because they can vary considerably depending on location and characteristics of the site. However, cost estimates based on local costs for irrigation equipment, labor, power, and construction should be used as a basis for comparing alternative distribution systems. Generally, mechanized or automated systems, such as center-pivot and solid set sprinklers, have relatively high capital costs and low labor costs compared with the manually moved sprinkler systems or manually operated surface systems. It is possible to automate surface systems.

Table 8-2 summarizes advantages and disadvantages of sprinkler distribution systems relative to surface systems. The physical features of the various distribution systems are described elsewhere [1,2].

Net Irrigation-Water Requirement

The net irrigation-water requirement (R) of a crop over a specified period of time is defined as the depth of water needed to meet the water loss through evapotranspiration (ET) of a crop achieving full production potential plus other beneficial use requirements such as leaching, seed germination, climate control, frost protection, and fertilizer or chemical application. Considering only ET and leaching requirements, the net irrigation requirement for any specified period of time is defined by the following equation:

$$R = (ET - P)(1 + \frac{LR}{100}) \qquad [8-1]$$

Table 8-1. Distribution systems and conditions of use.

Distribution system	Suitability and conditions of use: Crops	Topography	Soil	Water	Application efficiency[a] (%)
Sprinkler systems					
Portable hand move	Orchards, pasture grain, alfalfa, vineyards, low-growing vegetable and field crops	Max grade: 20%	Min IR[c]: 0.10 inch/hour WHC[d]: 3.0 inch	Quantity: NR[b] Quality: high TDS water can cause leaf burn	70-80
Wheel roll	All crops less than 3 ft high	Max grade: 15%	Min IR: 0.10 inch/hour WHC: 3.0 inch	Quantity: NR Quality: see above	70-80
Solid set	NR	NR	Min. IR: 0.05 inch/hour	Quantity: NR Quality: see above	70-80
Center pivot or traveling lateral	All crops except trees	Max grade: 15%	Min. IR: 0.30 inch/hour WHC: 2.0 inch	Quantity: large flows required Quality: see above	70-80
Traveling gun	Pasture, grain, alfalfa, field crops, vegetables	Max grade: 15%	Min. IR: 0.30 inch/hour WHC: 2.0 inch	Quantity: 100-1000 gal/min·unit Quality: see above	70-80
Surface systems					
Narrow graded border up to 15 ft wide	Pasture, grain alfalfa, vineyards	Max grade: 7% Cross slope: 0.2%	Min IR: 0.3 inch/hour Max IR: 6.0 inch/hour	Quantity: moderate flows required	65-85
Wide graded border up to 100 ft wide	Pasture, grain alfalfa, orchards	Max grade: 0.5-1% Cross slope: 0.2%	Min IR: 0.3 inch/hour Max IR: 6.0 inch/hour Depth: sufficient for required grading	Quantity: large flows required	65-85
Level border	Grain, field crops rice, orchards	Max grade: level Cross slope: 0.2%	Min IR: 0.1 inch/hour Max IR: 6.0 inch/hour Depth: sufficient for required grading	Quantity: moderate flows required	75-90
Straight furrows	Vegetables, row crops orchards, vineyards	Max grade: 3% Cross slope: 10% (erosion hazard)	Min IR: 0.1 inch/hour Max IR: NR if furrow length is adjusted to intake Depth: sufficient for required grading	Quantity: moderate flows required	70-85
Graded contour furrows	Vegetables, row crops orchards, vineyards	Max grade: 8% undulating Cross slope: 10% (erosion hazard)	Min IR: 0.1 inch/hour Max IR: NR if furrow length is adjusted to intake Non cracking soils required	Quantity: moderate flows required	70-85
Drip systems	Orchards, vineyards vegetables, nursery plants	NR	Min IR: 0.02 inch/hour	Quantity: NR	70-85

a. Based on good management and return of runoff water for surface systems.
b. NR = no restriction.
c. Infiltration rate.
d. Water-holding capacity.

Table 8-2. Advantages and disadvantages of sprinkler distribution systems relative to surface distribution systems [1].

Advantages	Disadvantages
1. Can be used on porous and variable soils.	1. Initial cost can be high.
2. Can be used on shallow soil profiles.	2. Energy costs are higher than for surface systems.
3. Can be used on rolling terrain.	3. Higher humidity levels can increase disease potential for some crops.
4. Can be used on easily eroded soils.	4. Sprinkler application of highly saline water can cause leaf burn.
5. Can be used with small flows.	5. Water droplets can cause blossom damage to fruit crops or reduce the quality of some fruit and vegetable crops.
6. Can be used where high water tables exist.	6. Portable or moving systems can get stuck in some clay soils.
7. Can be used for light, frequent applications.	7. Higher levels of preapplication treatment generally are required for sprinkler systems than for surface systems to prevent operating problems (clogging).
8. Control and measurement of applied water is easier.	8. Distribution is subject to wind distortion.
9. Tailwater control and re-application is minimized.	9. Wind drift of sprays increases the potential for public exposure to wastewater.

where

R = net irrigation-water requirement, inch

ET = crop evapotranspiration, inch

P = precipitation, inch

LR = leaching requirement, %

In Step 1 design, R is determined on a monthly basis for use in storage volume calculations. In this manual, design values of (ET - P) are based on a probability level of 90% exceedance (i.e., the value can be expected to be exceeded 90% of the time). Use of this value results in a conservative estimate of the required land area as discussed in the section on land area requirements.

Total Irrigation-Water Requirement

Because distribution systems do not apply water uniformly over the irrigated area and some water is lost during application, a depth of water (D) that is greater than the net irrigation-water requirement must be applied to ensure that the entire irrigated area receives the net irrigation-water requirement. The depth of water required is referred to as the total irrigation-water requirement and may be determined using the following equation:

$$D = \frac{R}{\left(\frac{E_u}{100}\right)} \qquad [8\text{-}2]$$

where D = total irrigation-water requirement, inch

R = net irrigation-water requirement

E_u = unit application efficiency for distribution systems, %

Table 8-1 reports the range of unit application efficiencies achieved in practice for each type of distribution system. When selecting a value (E_u) for use in design calculations, consideration must be given to site characteristics. For sprinkler systems, maximum application efficiencies can be expected at sites having cool climates, high relative humidity, and low average wind speeds, whereas minimum efficiencies can be expected in areas having hot climates, low relative humidity, and high average wind speeds. For surface distribution systems, maximum efficiency can be expected when soil permeability or intake rate is uniform throughout the length of the furrow or border, whereas minimum efficiencies can be expected when soil permeability is variable along the furrow or border.

In addition to application losses, some water can be lost during conveyance from storage reservoirs to distribution systems. Seepage losses in open channels should be estimated to determine a design value for conveyance efficiency (E_c) to use in computing the flow capacity of the water-delivery system.

Hydraulic Loading Rate

Hydraulic loading rate is the volume of wastewater applied per unit area of land per unit time. As previously stated, monthly units are used in Step 1 design. For Type 1 systems, the monthly hydraulic loading rate is the same as the monthly gross irrigation water requirement and is designated by the symbol $L_{w(1)}$. Tables 8-3 and 8-4, respectively, give examples of determination of monthly hydraulic loading rates for Type 1 systems with a double crop of corn and oats/vetch and with a permanent pasture grown at a site in the Central Valley, California.

Nitrogen Loading Limits

If percolating water from a reclaimed wastewater irrigation system will enter a potable groundwater aquifer, then the system should be designed so that the average concentration of nitrogen in the percolate does not exceed 10 mg/L N annually. It is assumed that all nitrogen is converted to nitrate. The procedure for estimating the hydraulic loading rate that will meet the percolate nitrogen limitation is based on a procedure presented in the EPA *Process Design Manual for Land Treatment of Municipal Wastewater* [1]. The procedure is as follows:

1. Calculate the allowable annual hydraulic loading rate based on nitrogen limits using the following equation:

$$L_{w(n)} = \frac{(C_p)(P - ET) + (U)\,(4.4)}{(1 - f)\,(C_n) - C_p} \qquad [8\text{-}3]$$

Table 8-3. Example of monthly hydraulic loading rate determination for Type 1 system with a double crop of corn + oat and vetch (expressed in inches).

(1) Month	(2) $(ET - P)_{90}$[a]	(3) $1 + \frac{LR}{100}$[b]	(4) $\frac{100}{E_u}$[c]	(5) = (2) x (3) x (4) $L_{w(1)}$[d]
Jan	-3.69	--	--	--
Feb	-2.59	--	--	--
Mar	-1.82	--	--	--
Apr	1.34	1.1	1.25	1.84
May	1.02	1.1	1.25	1.40
Jun	4.74	1.1	1.25	6.52
Jul	8.56	1.1	1.25	11.77
Aug	6.68	1.1	1.25	9.19
Sep	2.05	1.1	1.25	2.82
Oct	1.06	1.1	1.25	1.46
Nov	-2.10	--	--	--
Dec	-2.98	--	--	--
	12.27			35.00

a. 90% exceedance value--Davis, CA (see Chapter 5).

b. LR = 10%.

c. E_u = 80%.

d. $L_{w(1)}$ = hydraulic loading rate (type 1 system).

Table 8-4. Example of monthly hydraulic loading rate determination for Type 1 system with a permanent pasture crop (expressed in inches).

(1) Month	(2) $(ET - P)_{90}$[a]	(3) $1 + \frac{LR}{100}$[b]	(4) $\frac{100}{E_u}$[c]	(5) = (2) x (3) x (4) $L_{w(1)}$[d]
Jan	-4.00	--	--	--
Feb	-2.87	--	--	--
Mar	-2.02	--	--	--
Apr	2.10	--	1.25	2.63
May	5.47	--	1.25	6.87
Jun	6.87	--	1.25	8.55
Jul	7.43	--	1.25	9.29
Aug	6.31	--	1.25	7.89
Sep	4.80	--	1.25	6.00
Oct	1.71	--	1.25	2.14
Nov	-2.10	--	--	--
Dec	-3.30	--	--	--
Annual	20.31			43.37

a. 90% exceedance value--Davis, CA, ET pasture = potential evapotranspiration (ET_0) (See Chapter 5).

b. LR = 0%.

c. E_u = 80%.

d. $L_{w(1)}$ = hydraulic loading rate (type 1 system).

where $L_{w(n)}$ = allowable annual hydraulic loading rate based on nitrogen limits, inch/year

C_p = allowable nitrate concentration in percolating water, mg/L N (use 10 mg/L)

(P - ET) = normal year precipitation - evapotranspiration, inch/year

U = nitrogen uptake by crop, lb/acre·year

C_n = nitrogen concentration in applied wastewater, mg/L (after losses in preapplication treatment)

f = fraction of applied nitrogen removed by denitrification and volatilization (use 0.20 for design)

2. Compare the value of $L_{w(n)}$ with the annual sum of $L_{w(l)}$ calculated previously (see Tables 8-3 and 8-4). If $L_{w(n)}$ is equal to or greater than annual $L_{w(l)}$, use annual $L_{w(l)}$ for design. If $L_{w(n)}$ is less than annual $L_{w(l)}$, the designer has three options available to increase $L_{w(n)}$ sufficiently to meet the gross irrigation-water requirements or $L_{w(l)}$:
   a. Reduce the concentration of applied nitrogen (C_n) through preapplication treatment (see Chapter 2).
   b. Select a different crop with a higher nitrogen uptake (U) or use a double crop combination for annual crops.
   c. Demonstrate through use of models that sufficient mixing and dilution will occur with the existing groundwater to permit higher values of percolate nitrogen (C_p) to be used in Equation 8-3.

The above procedure is illustrated in Example 8-1 using the example Type 1 system illustrated in Table 8-4.

Example 8-1. Nitrogen loading limits.

<u>Conditions</u>

1. Reclaimed wastewater nitrogen concentration (C_n) = 25 mg/L N
2. Crop nitrogen uptake (U) = 270 lb/acre·year
3. Limiting percolate nitrate concentration (C_p) = 10 mg/L N
4. Normal year (P - ET) (see Chapter 5)

Example 8-1 (Continued).

5. Denitrification loss fraction (f) = 0.20

Calculations

1. Calculate allowable annual hydraulic loading based on nitrogen limits ($L_{w(n)}$) using Equation 8-3.

$$L_{w(n)} = \frac{(C_p)\ (P - ET) + (U)\ (4.4)}{(1 - f)\ (C_n) - C_p}$$

$$L_{w(n)} = \frac{(10)\ (-34.5) + (270)\ (4.4)}{(0.80)\ (25) - 10}$$

$$L_{w(n)} = 84.3 \text{ inch/year}$$

2. Compare $L_{w(n)}$ with annual $L_{w(1)}$ in Table 8-4:

$L_{w(n)} = 84.3$, which is greater than

$L_{w(1)} = 43.4$

Therefore, use $L_{w(1)}$ for design.

Field Area Requirements

The land area to which reclaimed wastewater is applied is termed the field area. The required field area is determined using the following equation:

$$A_w = \frac{(Q)(365 \text{ day/year})(3.06 \text{ acre ft/MG}) + \Delta V_s}{(L_w)\ \left(\frac{1}{12}\ \frac{\text{ft}}{\text{inch}}\right)} \qquad [8\text{-}4]$$

where A_w = field area, acre

Q = average daily wastewater flow (annual average), million gal/day

MG = million gallons

ΔV_s = net loss or gain in stored wastewater volume due to precipitation, evaporation, and seepage at the storage reservoir, acre ft/year

L_w = design annual hydraulic loading rate, inch/year.

The field area must first be estimated without considering the net loss or gain from storage. After the storage reservoir area is determined, the value of ΔV_s can be computed from precipitation and evaporation data. Field area then must be recalculated to account for ΔV_s. As stated previously, use of the 90% exceedance value for (ET - P) in determining irrigation water requirements results in larger land area requirements than would result from the use of normal year values of (ET - P). Thus, in years when (ET - P) exceeds $(ET - P)_{90}$, there will not be a sufficient amount of reclaimed wastewater to meet the gross irrigation-water requirement of the crop over the entire field area. In such years, the irrigator has the option of supplementing the reclaimed wastewater source with another source of irrigation water or practicing deficit irrigation on all or part of the field area. The concept of deficit irrigation has been discussed elsewhere [2].

Type 2 Systems

For Type 2 systems, the design steps are:

1. Selection of crop
2. Selection of distribution system
3. Determination of allowable percolation rate
4. Determination of maximum allowable monthly hydraulic loading rate
5. Determination of field area
6. Determination of storage requirements

Crop Selection

Crops that are most compatible with Type 2 systems are those having high nitrogen uptake capacity, high evapotranspiration demand, high tolerance for moist soil conditions, low sensitivity to wastewater constituents, and minimum management requirements. The crops having all or most of these characteristics include certain perennial forage grasses, turf grasses, and some tree species. Forage crops that are used successfully include reed canarygrass, tall fescue, perennial ryegrass, Italian ryegrass, orchardgrass and bermudagrass. Reed canarygrass and tall fescue have very high moisture tolerances. Grasses grown for rotated permanent pasture have the advantage of no downtime requirement for harvesting as long as animal rotation is coordinated with the irrigation schedule. The most common tree crops used for Type 2 systems have been mixed hardwoods and pines. A more complete discussion of crop selection criteria is presented in Chapter 6.

Distribution System Selection

The criteria used in selecting a distribution system are basically the same for both Type 1 and Type 2 systems. However, for Type 2 systems, the unit application efficiency of the distribution system is not a major consideration, because the depth of applied water is in excess of the crop's gross irrigation-water requirement.

Allowable Percolation Rate

Water applied in excess of the available water capacity of the soil will percolate beyond the root zone and enter underlying groundwater or drainage systems. This percolate is referred to as deep percolation. In some Type 1 systems, a certain amount of deep percolation may be required to leach salts from the root zone (see Chapter 7). However, in Type 2 systems, deep percolation in excess of any leaching requirement serves no use except treatment and disposal of the applied reclaimed wastewater. Of course, there is a maximum amount of deep percolation that can be allowed and still meet the objective of producing a marketable crop without causing management problems or nuisance conditions or impairing the beneficial use of the groundwater.

The design value for allowable percolation rate is based on the saturated permeability of the most restrictive layer in the top 8 ft (2.4 m) of the soil profile. In general, Type 2 systems should not be used at sites where the limiting permeability is less than 0.2 inch/hour (0.51 cm/hour). It is possible to use sites with lower permeabilities, but careful management is required to prevent nuisance conditions (standing water, seepage, mosquitos, etc.) from developing.

The procedure used to determine the allowable percolation rate is a modified version of the procedure presented in the EPA *Process Design Manual* [1]. The procedure is as follows:

1. Determine by field test the minimum clear water saturated permeability of the soil profile. If the minimum

permeability is variable over the site, determine a weighted average based on soil types (see Chapter 4).

2. Establish a maximum daily percolation rate in the range of 4% to 6% of the minimum soil profile permeability. Values of up to 10% can be used for soil permeabilities greater than 2.0 inches/hour (5.1 cm/hour). Percentages at the low end of the range should be used when the limiting permeability is less than 0.6 inch/hour (1.5 cm/hour) or when the soil permeability is poorly defined. The daily percolation rate is determined as follows:

$$W_{p(daily)} = (\text{permeability, inch/hour}) \times (24\ \text{hours/day}) \times (0.04\ \text{to}\ 0.06)$$

3. Calculate the design monthly percolation rate, making adjustments for periods of nonoperation. Nonoperating periods may be necessary for:
   a. Harvesting or cultural procedures.
   b. Precipitation. No adjustment is necessary, because precipitation is already factored into the water balance equation.
   c. Freezing temperatures. No operation should be allowed on days during months when the mean temperature is less than 25°F (4°C). Mean temperature data for California stations are reported elsewhere [3], or detailed climatological data for each county are available in each county at the Cooperative Extension Offices.
4. Calculate the design monthly percolation rate as follows:

$$W_{p(monthly)} = [W_{p(daily)} \times (\text{no. of operating days/month})]$$

An example of the procedure is provided in Table 8-5, p. 8-19.

Maximum Allowable Hydraulic Loading Rate

Determination of the maximum allowable monthly hydraulic loading rate is based on the general water balance equation with rates on a monthly basis. Because runoff of applied water is not allowed to occur, the water balance equation reduces to the following:

$$L_w = (ET - P) + W_p \qquad [8\text{-}5]$$

where L_w = wastewater hydraulic loading rate, inch/month
$ET - P$ = net evapotranspiration, inch/month
W_p = allowable percolation rate, inch/month

The steps in the procedure are:

1. Estimate the monthly (ET - P) based on a 90% exceedance value (see Chapter 5).
2. Calculate the hydraulic loading rate for each month using Equation 8-5 and monthly values for (ET - P) and W_p.
3. The monthly hydraulic loading rates are summed to yield the allowable annual hydraulic loading rate for Type 2 systems, annual $L_{w(2)}$. The computation procedure is illustrated for a pine tree crop by example in Table 8-5.

Nitrogen Loading Limits

The calculated value of annual $L_{w(2)}$ must be compared with the allowable hydraulic loading rate based on nitrogen limitations as described previously for Type 1 systems.

If annual $L_{w(2)}$ exceeds $L_{w(n)}$, and if $L_{w(n)}$ cannot be increased by increasing crop nitrogen uptake or reducing the wastewater nitrogen concentration, then $L_{w(n)}$ must be used for the design annual loading rate. Maximum monthly hydraulic loading rate values can then be calculated by multiplying previously determined monthly hydraulic loading rates by the ratio annual $L_{w(n)}/L_{w(2)}$.

Field Area Requirements

The minimum field area that can be used for a Type 2 system may be computed using Equation 8-4 with the maximum allowable annual hydraulic loading rate ($L_{w(2)}$ or $L_{w(n)}$, whichever is less). Two cases are considered in determining the actual field area used for design of Type 2 systems. In the first case, the objective is to minimize the field area to minimize the capital cost of land purchase or lease. In this case, the minimum field area is used as the design field area. In the second case, land is available for a system without cost, but the area available is less than that calculated for a Type 1 system.

The available area must be compared with the minimum field area for Type 2 systems. If the available area is greater than the minimum area, then the available area may be used as the design field area. Design monthly hydraulic loading rate values can then be calculated by multiplying previously determined maximum monthly values by the ratio minimum field area/available field area.

Other Land Area Requirements

For both Type 1 and Type 2 systems, land in addition to the field area may also be required for preapplication treatment facilities, service roads, buffer zones, and storage reservoirs. Buffer zone requirements are discussed in this section. Other land area requirements are determined by standard engineering practice not included in this manual.

In California, the width of buffer zones around dwellings, public roads, wells, and reservoirs is prescribed by the Regional Water Quality Control Boards based on recommendations from the state and county health departments. In some cases, fringe or perimeter planting of trees and shrubs can be used to reduce buffer zone requirements and improve neighbor acceptance of the project. A multistoried canopy will reduce spray drift, improve visual appearance, and provide wildlife habitat. Evergreen species are the best selection if year-round operation is planned.

Storage Requirements

The procedure used to determine storage requirements is the same for Type 1 and Type 2 systems. The approach used is adapted from the EPA *Process Design Manual* [1]. In this procedure, an estimate of the storage volume requirement is first made using a water balance computation. The final design storage volume is then determined by adjusting the estimated volume for net gain or loss due to precipitation or evaporation.

<u>Estimation of Storage Volume Requirements</u>

The steps in the estimating procedure are illustrated using the example data from Table 8-5 and an average daily flow of 1 million gal/day:

1. Tabulate the design monthly hydraulic loading rate as indicated in Table 8-5.
2. Convert the monthly hydraulic loading rate values to units of volume using the following relationship. Tabulate the results as indicated in Table 8-6.

$$V_w = \frac{(A_w)(L_w)}{12} \qquad [8\text{-}6]$$

where V_w = volume of monthly hydraulic loading rate, acre ft
A_w = estimated field area, acres
L_w = monthly hydraulic loading rate, inch

3. Determine or predict the actual volume of wastewater available each month in units of acre ft and tabulate the values as indicated in Table 8-6. In some communities, influent wastewater flow varies significantly with the time of year, as indicated in the example values in Table 8-6. The values used for Q_m should reflect monthly flow variation based on historical records.
4. Compute the net change in storage each month by subtracting the monthly hydraulic loading from the available wastewater in the same month.
5. Compute the cumulative storage at the end of each month by adding the change in storage during one month to the accumulated quantity from the previous month. The computation should begin with the reservoir empty at the beginning of the largest storage period. This month is usually October or November. The largest cumulative storage value is the estimated storage volume requirement to be used for final design calculations.

Table 8-5. Water balance to determine hydraulic loading rates for a Type 2 system with a tree crop (in inches).

(1) Month	(2) $(ET - P)_{90}$[a]	(3) W_p[b]	(4)=(2)+(3) $L_{w(2)}$[c]
Jan	-3.7	5.8	2.1
Feb	-2.6	5.8	3.2
Mar	-1.8	5.8	4.0
Apr	3.0	5.8	8.8
May	6.6	5.8	12.4
Jun	8.2	5.8	14.0
Jul	8.9	5.8	14.7
Aug	7.6	5.8	13.4
Sep	5.8	5.8	11.6
Oct	2.4	5.8	8.2
Nov	-1.9	5.8	3.9
Dec	-3.0	5.8	2.8
Annual	29.5	69.6	99.1

a. 90% exceedance value of evapotranspiration precipitation for pine trees--Davis, Calif.

b. Allowable percolation based on a limiting soil permeability of 0.2 inch/hour. $W_{p(max)}$ = (0.2 inch/hour)(24)(30)(0.04) = 5.8. No nonoperating days are assumed for trees.

c. $L_{w(2)}$ = hydraulic loading rate (type 2 system).

Table 8-6. Estimation of storage volume requirements using water balance calculations (in acre ft).

(1) Month	(2) V_w wastewater hydraulic loading[ab]	(3) Qm available wastewater[b]	(4)=(3)-(2) ΔS Change in storage	(5) $\Sigma\Delta S$ Cumulative storage
Oct	92.5	96.1	3.6	0.1[c]
Nov	44.0	73.4	29.4	3.6
Dec	31.7	76.2	44.5	33.0
Jan	23.7	75.4	51.7	77.5
Feb	36.2	73.4	37.2	129.2
Mar	45.1	94.8	49.7	166.4
Apr	99.2	91.8	-7.4	216.1
May	139.6	95.0	-44.6	208.7
Jun	157.7	110.2	-47.5	166.1
Jul	165.5	110.2	-55.3	116.6
Aug	151.0	110.2	-40.8	61.3
Sep	130.6	110.2	-20.4	20.5
Annual	1,116.8	1,116.9		

a. Computed from equation 8-6 using L_w values from Table 8-5 and

$$A_w = \frac{(1)(365)(3.06)}{99.1\ (\frac{1}{12})} = 135.3 \text{ acres.}$$

b. Based on a field area of 135.3 acres and average daily flow of 1 million gal/day with seasonal variations.

c. Rounding error. Assume zero.

d. Maximum storage month.

Final Design Storage Volume Calculations

The mass balance procedure is illustrated by Example 8-2 using example data from Table 8-5.

Example 8-2. Calculations to determine final storage volume requirements.

Calculations

1. Using the estimated storage volume and an assumed storage reservoir depth compatible with local conditions, calculate a required surface area for the storage reservoir:

$$A_s = \frac{V_{s(est)}}{d_s}$$

where A_s = area of storage reservoir, acre
$V_{s(est)}$ = estimated storage volume, acre ft
d_s = assumed reservoir depth, ft

For the example, assume d_s = 12 ft

$$A_s = \frac{216.1}{12}$$

$$= 18 \text{ acres}$$

2. Calculate the monthly net volume of water gained or lost from storage due to precipitation, evaporation, and seepage:

$$\Delta V_s = \frac{(P - E_{pond} - \text{seepage})(A_s)}{(12 \text{ inches/ft})}$$

where ΔV_s = net gain or loss in storage volume, acre ft
$(P - E_{pond})_{90}$ = 90% exceedance falue for precipitation - pond evaporation, inch
A_s = storage reservoir area, acre

The value for $(P - E\ pond)_{90}$ may be estimated by taking the average of $(P - ET_o)_{90}$ and $(P-ET_{trees})_{90}$, or it may be computed directly using the procedures in Chapter 5.

For the example, assume seepage = 0.

Results are tabulated in column 2 of Table 8-7.

Example 8-2 (Continued).

3. Tabulate the volume of wastewater available each month (Q_m) accounting for any expected monthly flow variations (see column 3).
4. Calculate an adjusted field area to account for annual net gain/loss in storage volume:

Table 8-7. Final storage volume requirement calculations (in acre ft).

(1)	(2)	(3)	(4)	(5)=(2)+(3)-(4)	(6)
Month	ΔV_s Net gain/loss	Q_m Available wastewater	V_w Applied wastewater	ΔS Change in storage	$\Sigma\Delta$ Cumulative storage
Oct	-3.1	96.4	89.3	3.7	0.0
Nov	3.0	73.4	42.4	34.0	3.7
Dec	4.7	76.2	30.4	50.5	37.8
Jan	5.8	75.4	22.9	58.3	88.3
Feb	4.1	73.4	34.9	42.6	146.6
Mar	2.9	94.8	43.5	54.2	189.2
Apr	-3.8	91.8	96.0	-8.0	243.4[a]
May	-9.0	95.0	135.1	-49.1	235.4
Jun	-11.3	110.2	152.6	-53.7	186.3
Jul	-12.3	110.2	160.2	-62.3	132.6
Aug	-10.4	110.2	146.0	-46.2	70.3
Sep	-7.9	110.2	126.4	-24.1	24.1
Annual	-37.3	1,116.9	1,079.7		

a. Maximum design storage volume.

Example 8-2 (Continued).

$$A_w' = \frac{\Sigma Q_m + \Sigma \Delta V_s}{(L_w)\ (\frac{1}{12})}$$

where A_w' = adjusted field area, acre
$\Sigma \Delta V_s$ = annual net storage gain/loss, acre ft
ΣQ_m = annual available wastewater, acre ft
L_w = design annual hydraulic loading rate, inch/year.

For the example:

$$A_w = \frac{1,116.9 - 37.3}{(99)\ (\frac{1}{12})}$$

$$= 131 \text{ acres}$$

Note: The final design calculation reduced the field area from 135 acres to 131 acres.

5. Calculate the adjusted monthly volume of applied wastewater using the design monthly hydraulic loading rate and adjusted field area:

$$V_w = (L_w)(A_w')/12 \text{ inches/ft}$$

where V_w = monthly volume of applied wastewater, acre ft
L_w = design monthly hydraulic loading rate, inch
A_w' = adjusted field area, acre

Results are tabulated in column 4 of Table 8-7.

6. Calculate the net change in storage each month by subtracting the monthly applied wastewater (V_w) from the sum of available wastewater (Q_m) and net storage gain/loss (ΔV_s) in the same month. Results are tabulated in Column 5 of Table 8-7.

7. Calculate the cumulative storage volume at the end of each month by adding the change in storage during one month to the accumulated total from the previous month. The computation should begin with the cumulative storage equal to zero at the beginning of the largest storage period. The maximum monthly cumulative volume is the storage volume requirement used for design. Results are tabulated in Column 6 of Table 8-7.

Design storage volume = 243.4 acre ft

Off-line Storage

In some cases, it may be allowable to irrigate with primary effluent, but primary effluent requires additional treatment prior to storage (see Chapter 2). By arranging the piping so that storage can be bypassed, it is possible to irrigate directly with primary effluent. This arrangement is termed off-line storage and is shown schematically in Figure 8-2.

STEP 2 DESIGN--IRRIGATION REQUIREMENTS AND SCHEDULING

The irrigation system design parameters common to all distribution systems to be determined during Step 2 design are:

1. Depth of water applied per irrigation
2. Irrigation frequency

A Step 2 design example is presented at the end of this section for Type 1 and Type 2 systems.

Depth of Water Applied per Irrigation

The depth of water applied during an irrigation event is the total irrigation requirement per irrigation. Determination of this design parameter requires knowledge of two factors: (1) the available water capacity (AWC) of the soil in the root zone of the plant and (2) the management-allowed deficit of water in the root zone before irrigation.

The water available for plant use is defined as the difference in soil water content at "field capacity" and the "wilting point." The moisture remaining in the soil at 15 bars tension is referred to as the wilting point moisture.

The AWC varies primarily as a function of soil texture. The normal ranges of AWC for California soils of different textures are reported in Table 8-8. Actual measured values are preferred, but the values in Table 8-8 may be used in the absence of measured values. The total available water (TAW) in the root zone may be computed by multiplying the AWC by the depth of the root zone.

Information on soil texture, depth, and available water capacity (AWC) is available from published soil surveys prepared by the USDA Soil Conservation Service and Cooperative Extension. Reports are available at most city and county libraries or from the local office of the SCS or Cooperative Extension.

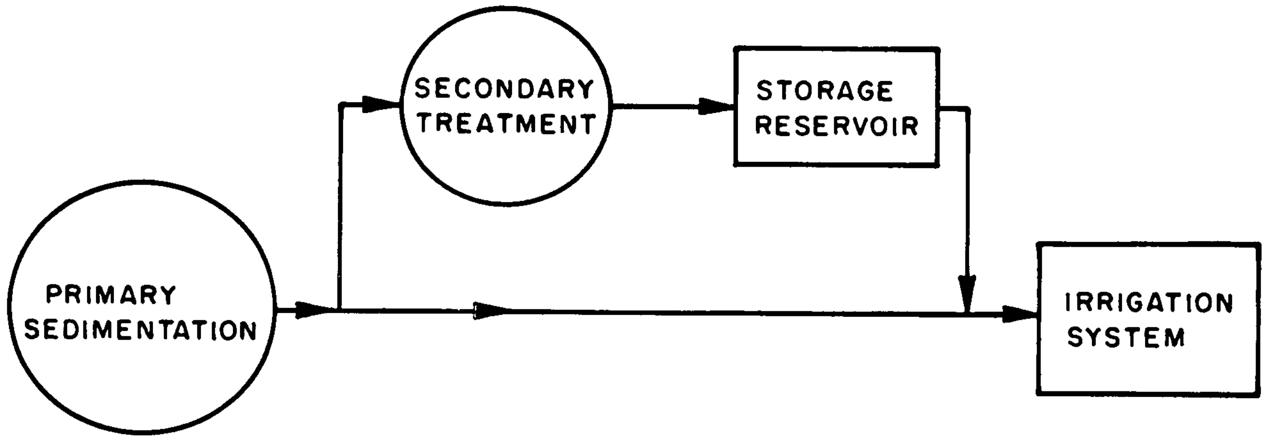

Figure 8-2. Schematic flow diagram for off-line storage.

Table 8-8. Available water capacity for California soils related to texture (inch/ft).

Textural class	Available water capacity
Peat and muck	2.4 - 3.6
Clay > 60%	1.4 - 1.8
Clay < 60%	1.7 - 2.0
Silty clay	1.7 - 2.0
Sandy clay	1.6 - 2.0
Silty clay loam	2.0 - 2.5
Clay loam	2.0 - 2.5
Sandy clay loam	1.7 - 2.2
Silt loam	1.8 - 2.4
Loam	1.7 - 2.2
Very fine sandy loam	1.7 - 2.0
Fine sandy loam	1.6 - 1.8
Sandy loam	1.2 - 1.6
Coarse sandy loam	1.1 - 1.4
Loamy very fine sand	1.1 - 1.3
Loamy fine sand	1.0 - 1.3
Loamy sand	0.7 - 1.0
Loamy coarse sand	0.6 - 0.8
Very fine sand	0.7 - 1.0
Fine sand	0.6 - 1.0
Sand	0.6 - 1.0
Coarse sand	0.4 - 0.8

The percentage or corresponding depth of the total available soil water that is allowed to be used by the plant before an irrigation is scheduled is referred to as the management-allowed deficit (MAD). The MAD is usually the maximum depletion that will not result in reduced crop yield or quality. The usual range of MAD is from 30% to 50% of the available water from the root zone of the crop. For annual crops, the MAD varies by stage of growth and is reduced during critical stages of plant growth. Cooperative Extension advisers should be consulted for recommended values of MAD for specific crops.

Irrigation systems are normally designed to "refill" the soil water "reservoir" when the amount of water extracted from the "reservoir" equals the MAD. This net moisture to be replaced by irrigation may be calculated using the following equation:

$$D_{(net)} = TAW \times \left(\frac{MAD}{100}\right) \qquad [8\text{-}7]$$

where $D_{(net)}$ = net depth of water to be replaced by irrigation, inch

TAW = total available water in the plant root zone, inch

MAD = management allowed deficit, %

To determine the depth of water to be applied during an irrigation for Type 1 systems, the factors leaching requirement (LR) and unit application efficiency (E_u) must be considered. These factors are discussed in Step 1 design. The total depth of application may be computed using the following equation:

$$D = \frac{D_{(net)} + \left(D_{net} \times \frac{LR}{100}\right)}{\left(\frac{E_u}{100}\right)} \qquad [8\text{-}8]$$

where D = depth of water applied during the irrigation, inch

$D_{(net)}$ = net depth of water to be replaced by the irrigation, inch

LR = leaching requirement, %

E_u = unit application efficiency, %

For Type 2 systems, the total depth of water applied per irrigation depends on the monthly hydraulic loading rate determined in Step 1 design and the irrigation frequency for the month according to the following equation:

$$D = L_{w(m)} \times \frac{t_m}{30} \qquad [8\text{-}9]$$

where D = total depth of water applied per irrigation, inch

$L_{w(m)}$ = monthly hydraulic loading rate for month (m)

t_m = maximum time between irrigations for month (m), day

Irrigation Frequency

Irrigation frequency refers to the number of days between irrigations. In practice, growers schedule irrigations or determine irrigation frequency by one of three techniques:

1. Fixed calender schedules developed by growers based on experience.
2. Field monitoring of the soil moisture content using instruments (tensiometers, resistance blocks, neutron probe) or soil sampling.
3. Water balance calculations using soil available water capacity and evapotranspiration data.

For purposes of design, the third method, water balance calculations, is used to determine irrigation frequency. The design of the irrigation system is based on the minimum irrigation frequency during the period of peak evapotranspiration demand. The irrigation frequency at peak ET can be calculated from the $D_{(net)}$ and the peak ET rate using the following equation:

$$t_p = \frac{D_{(net)}}{ET_{(peak)}} \qquad [8\text{-}10]$$

where t_p = maximum time between irrigations at peak ET, day

$D_{(net)}$ = net depth of water to be replaced by irrigation, inch

$ET_{(peak)}$ = peak daily ET rate of the crop, inch/day

Procedures for estimating the peak daily ET rate of the crop during any month are described in detail in Chapter 5. The value of $D_{(net)}$ must be known to use the procedure in Chapter 5 for estimating $ET_{(peak)}$.

In general, irrigation systems should be designed so that the irrigation cycle can be completed in less time than t_p to allow a safety factor for system down time and for cultural operations that must be performed. If the system must run continuously in order to meet the crop needs, down time may result in crop damage and reduced yields. A 25% design safety factor is usually considered adequate, although some cultural practices, such as haying, may require as much as 50% reduction in time allowed between irrigations. Thus, the design irrigation frequency may be calculated as follows:

$$t_d = 0.75\ t_p \qquad [8\text{-}11]$$

where t_d = design time to complete irrigation at peak ET, day

t_p = maximum time between irrigations at peak ET, day

The time between irrigations for any month can be calculated using the following equation:

$$t_m = \frac{D_{(net)}}{ET_{(pm)}} \qquad [8\text{-}12]$$

where t_m = maximum time between irrigations during month (m), day

$D_{(net)}$ = net depth of water to be replaced by irrigation, inch

$ET_{(pm)}$ = peak daily ET rate during month (m), inch/day

For Type 2 systems, equation 8-12 can be used to determine monthly values of t_m to be used in equation 8-9 when calculating (D), total depth of water applied per irrigation.

Example calculations of irrigation requirement and frequency are given in Examples 8-3 and 8-4, respectively.

Example 8-3. Calculation of irrigation requirement and frequency for Type 1 system with a corn crop.

Conditions

1. Effective rooting depth of corn = 4 ft
2. AWC of loam soil = 2 inches/ft
3. MAD at peak ET = 50%
4. Leaching requirement (LR) = 10%
5. Application efficiency (E_a) = 80%

Calculations

1. Determine total available water in root zone

$$\begin{aligned} TAW &= (AWC)\ (\text{depth of root zone}) \\ &= (2\ \text{inches/ft})\ (4\ \text{ft}) \\ &= 8\ \text{inches} \end{aligned}$$

2. Calculate the net depth of applied water

$$\begin{aligned} D_{(net)} &= (TAW)\ \left(\frac{MAD}{100}\right) \\ &= (8\ \text{inches})\ \left(\frac{50}{100}\right) \\ &= 4\ \text{inches} \end{aligned}$$

3. Determine depth of water applied during one irrigation:

$$D = \frac{D_{(net)} + \left(D_{net} \times \frac{LR}{100}\right)}{\frac{Ea}{100}}$$

$$D = \frac{4 + \left(4 \times \frac{10}{100}\right)}{\frac{80}{100}}$$

$$D = 5.5\ \text{inches}$$

4. Determine the 10-year frequency peak daily ET for peak month (July) using Figure 5-8 and the value of $D_{(net)}$ (see Chapter 5).

Example 8-3 (Continued).

5. Determine the maximum time between irrigations at peak ET

$$t_p = \frac{D_{net}}{ET_{peak}}$$

$$t_p = \frac{4.0}{0.383}$$

$t_p = 10.4$ days <u>Use 10 days</u>

6. Determine the design time to complete irrigation of the total field area:

$t_d = 0.75\ t_p$

$t_d = 7.5$ days <u>Use 7 days</u>

Example 8-4. Calculation of irrigation requirement and frequency for Type 2 system with a pine tree crop.

<u>Conditions</u>

1. Effective rooting depth = 5 ft
2. AWC of clay loam soil = 2 inches/ft
3. MAD at peak ET = 50%

<u>Calculations</u>

1. Determine total available water in root zone:

TAW = (AWC) (depth of root zone)

= (2 inches/ft) (5)

= 10 inches

2. Calculate the net depth of water applied per irrigation:

$$D_{(net)} = (TAW)\left(\frac{MAD}{100}\right)$$

$$= (10 \text{ inches})\left(\frac{50}{100}\right)$$

$$= 5 \text{ inches}$$

3. Determine the 10-year frequency peak daily ET for the month (July) using Figure 5-8 and the value for $D_{(net)}$. Values for each month are calculated in the same manner.

$ET_{pm} = 0.39$ inches/day

Example 8-4 (Continued).

4. Determine the maximum time between irrigations for the month (July).

$$t_m = \frac{D_{(net)}}{ET_{pm}}$$

$$tm = \frac{5 \text{ inch}}{0.39}$$

$$t_m = 12.94 \quad \underline{\text{Use 13 days}}$$

5. Determine depth of applied water per irrigation for the month (July). Values for other months are calculated in the same manner (see Table 8-5).

$$D = (L_w)\left(\frac{t_m}{30}\right)$$

$$= (14.7 \text{ inches})\left(\frac{13}{30}\right)$$

$$= 6.4 \text{ inches}$$

6. Determine the design time to complete irrigation of the total field area:

$$t_d = 0.75\ t_m$$

$$t_d = 0.75\ (13)$$

$$t_d = 9.7 \text{ days} \quad \underline{\text{Use 10 days}}$$

STEP 3 DESIGN--DETAILED SYSTEM DESIGN

A summary of references for design of various system components is given in Table 8-9. Design procedures are described in this section in sufficient detail so that system flow capacity can be estimated. Also, the USDA Soil Conservation Service has prepared practice standards covering several aspects of design.

Stationary Sprinkler Systems

Stationary sprinkler systems include solid set systems and periodical lateral move systems (wheel move, hand move laterals). Design parameters for stationary sprinkler systems include the following:

Table 8-9. Summary of references on detailed design of irrigation systems.

Irrigation system component	Reference numbers
General	[2] [6] [10]
Stationary sprinklers	[4] [11] [12]
Moving sprinklers	[5] [11] [12]
Furrow irrigation	[8] [13]
Graded border irrigation	[8] [14]
Drip irrigation	[15]
Tailwater return	[16]
Drainage system	[17] [18] [19]
Storage reservoirs	[20]

1. Application rate
2. Application period
3. Irrigated area
4. System flow capacity
5. Sprinkler selection and spacing
6. Lateral sizing and layout

Application Rate

Application rate of a sprinkler system is the rate at which water is applied expressed in units of inch/hour. Stationary sprinkler systems are designed so that the average application rate over the irrigated area is less than the basic intake rate of the surface soil to prevent runoff. Application rates can be increased when a full crop cover is present. The increase should not exceed 100% of the bare soil application rate [1]. Recommended reductions in application rate for sloping terrain are given in Table 8-10. A practical minimum design application rate is 0.2 inch/hour (0.5 cm/hour).

Table 8-10. Recommended reductions in application rates due to grade [4].

Grade	Application rate reduction,%[a]
0-5	0
6-8	20
9-12	40
13-20	60
over 20	75

a. Percent of level ground application rate.

Application Period

The period of time over which (D) is applied is the application period, and it is a function of (D) and the average rate of application and may be calculated using the following equation:

$$T_a = \frac{D}{I} \qquad [8\text{-}13]$$

where T_a = application period, hour
D = total depth of water applied, inch
I = average application rate, inch/hour

The application rate may be adjusted to yield an application period that is convenient to the operator and compatible with working hours.

Irrigated Area

For stationary systems, water is not normally applied to the entire field area in a single irrigation. Rather, the field area is divided into application plots or zones and water is applied to one zone at a time. Application is rotated among the zones so that the entire field area receives one irrigation within the time period (t_d). The minimum size of the irrigated area may be calculated using the following equation:

$$A_{i(m)} = \frac{(A_w)(T_a)}{(t_d)(24)} \qquad [8\text{-}14]$$

where $A_{i(m)}$ = minimum irrigated area, acre
A_w = total field area, acre
T_a = application period, hour
t_d = design time to complete irrigation, day

Larger irrigated areas can be used, which will result in lower labor requirements but a larger system flow capacity, as described in the next section.

System Flow Capacity

The maximum flow capacity of the system must be determined so that components, such as pipelines and pumping stations, can be sized properly. For stationary sprinkler systems with a constant application rate, the flow capacity of the system can be computed using the following formula:

$$Q = (A_i)(I)(453) \qquad [8\text{-}15]$$

where Q = system flow capacity, gal/min
A_i = irrigated area, acre
I = application rate, inch/hour

Sprinkler Selection and Spacing

For stationary sprinkler systems, the application rate can be expressed as a function of the sprinkler discharge capacity, the spacing of the sprinklers along the lateral, and the spacing of the laterals along the main according to the following equation:

$$I = \frac{(q_s)(96.3)}{(S_s)(S_L)} \qquad [8\text{-}16]$$

where I = application rate, inch/hour
q_s = sprinkler discharge rate, gal/min
S_s = sprinkler spacing along lateral, ft
S_L = lateral spacing along main, ft

Sprinkler selection and spacing determination involves an iterative process. The usual procedure is to select a sprinkler and lateral spacing, then determine the sprinkler discharge capacity required to provide the design application rate at the selected spacing. The required sprinkler discharge capacity may be calculated using Equation 8-13. Manufacturers' sprinkler performance data are then reviewed to determine the nozzle sizes, operating pressures, and wetted diameters of sprinklers operating at the desired discharge rate. The wetted diameters are then checked with the assumed spacings for conformance with spacing criteria. Recommended spacings are based on a percentage of the wetted diameter and vary with the wind conditions. Recommended spacing criteria are given in Table 8-11. References in Table 8-9 should be consulted for details.

Table 8-11. Recommended spacing of sprinklers [4].

Average wind speed	Spacing[a]
mile/hour	% of wetted diameter
0-7	40 (between sprinklers)
7-10	65 (between laterals)
>10	30 (between sprinklers) 50 (between laterals)

a. These values are for high pressure sprinklers. Newer low pressure sprinklers (30 to 40 psi) normally have 10-ft less throw, and an adjustment in lateral spacing is required.

Lateral Sizing and Layout

The size of mainlines and sprinkler lateral pipes must be selected such that the friction loss at the design flow is limited to a predetermined amount. A general practice is to limit all hydraulic losses (static and dynamic) in the main plus lateral to 15% of the operating pressure of the sprinklers. This will result in sprinkler discharge variations of about 10% along any lateral.

When determining the position or layout of the laterals in the field, the topography and the wind direction must be considered. The references in Table 8-9 should be consulted for details.

Traveling Gun Sprinklers

Design parameters for traveling gun sprinklers include:

1. Application rate
2. Irrigation area/unit
3. Unit sprinkler discharge capacity
4. Travel lane spacing
5. Travel speed
6. Number of units
7. System flow capacity

8. Pipe and hose size
9. System layout

Application Rate

Application rates for moving sprinkler systems, such as center-pivot and traveling gun sprinklers, vary with time and space and are necessarily higher than rates for stationary systems, because water is applied at any one point for only a fraction of the total time of irrigation. For traveling guns, the application rate is a function of the sprinkler nozzle characteristics and may be determined from manufacturer performance tables. The minimum design application rate for the smaller sprinkler guns is in the range of 0.25 to 0.30 inch/hour. The largest units have application rates approaching 0.5 inch/hour. It should be noted that part-circle sprinklers are often used to avoid wetting the travel lane ahead of the traveling unit, but the application rate increases in proportion to the reduction in the extent of revolution. Application rates in excess of the basic intake rate of the soil or vegetated surface can be used if allowances are made for (1) higher intake rates at the beginning of application and (2) temporary storage of water on the soil surface. Recommended allowances for surface storage for different slopes are presented in Table 8-12. When surface storage capacity is exceeded, runoff will occur.

Table 8-12. Allowable surface storage values for various slopes [5].

Slope (%)	Allowable surface storage (inch)
1-3	0.3
3-5	0.1

Other Design Parameters

The steps involved in determining the remaining design parameters are outlined as follows:

1. Estimate the area to be irrigated by a single unit. The practical maximum design value is about 80 acres.
2. Estimate the number of hours per day that a unit will be in operation, allowing time (1 hour minimum) to move the unit at the end of each travel lane. This value will depend on individual requirements, but maximum values should not exceed 20 to 22 hours/day.
3. Estimate the sprinkler discharge capacity using the following formula:

$$q_s = \frac{(435)(D_{(total)})(A_i)}{(t_p)\ (T_a)} \qquad [8\text{-}17]$$

where q_s = sprinkler discharge capacity, gal/min
$D_{(total)}$ = depth of water applied per irrigation, inch
A_i = area irrigated per unit
t_p = time between irrigations at peak ET, day
T_a = length of operating time per day, hour

4. Select from manufacturer performance tables a sprinkler size and operating pressure that will provide the estimated discharge capacity. Operating pressures should be greater than 80 lbs/inch^2.
5. Check application rate of selected sprinkler against the basic intake rate of the soil or vegetated surface. Reduce the selected sprinkler discharge capacity as necessary so that the application rate will be compatible with the soil intake rate and surface storage capacity and so that runoff will not occur.
6. Determine the design lane spacing based on the wetted diameter of the selected sprinkler using the spacing criteria given in Table 8-13.

Table 8-13. Recommended maximum lane spacing for traveling gun sprinklers.

Wind Speed (mile/hour)	Lane spacing (% of wetted diameter)
0	80
1-5	70-75
6-10	60-65
>10	50-55

7. Calculate the travel speed of the unit using the following formula:

$$S_p = \frac{(q_s)(1.6)}{(S_t)(D)} \qquad [8\text{-}18]$$

where S_p = travel speed, ft/min
q_s = sprinkler capacity, gal/min
S_t = space between travel lanes, ft
D = depth of water applied per irrigation, inch

8. Calculate the actual area irrigated per unit using the following equation:

$$A_i = \frac{(S_t)(L_t)(t_d)}{43{,}560} \qquad [8\text{-}19]$$

where A_i = area irrigated per unit, acre
S_t = lane spacing, ft
L_t = average travel distance per day, ft
t_d = design time to complete irrigation, day (see equation 8-11)

9. Calculate the total number of units required for the complete system using the following equation:

$$N_u = \frac{A_w}{A_i} \quad [8\text{-}20]$$

where N_u = total no. of units required

A_w = field area, acre

A_i = area irrigated per unit

10. Determine the flow capacity for the total system as follows:

$$Q = (q_s)(N_u) \quad [8\text{-}21]$$

where Q = system flow capacity, gal/min

11. Select sizes for supply pipe and flexible hose to minimize total capital and operating costs.
12. Layout mainlines to minimize length and layout travel lanes perpendicular to the prevailing wind.

Center-Pivot Sprinklers

Design parameters for center-pivot systems include:

1. Application rate
2. Irrigated area per unit
3. Water flow per unit
4. Rotational speed of the lateral
5. Sprinkler sizing and spacing

Center-pivot systems are not widely used in California and therefore are not discussed here. System design has been discussed by Dillon et al. [5].

Surface Systems

Furrow Distribution

The design procedure for furrow systems is empirical and is based on past experience with good irrigation systems and field evaluation of operating systems. For more detailed design procedures, the designer is referred to references in Table 8-9.

The design variables for furrow systems include:

1. Furrow grade
2. Furrow spacing

3. Furrow length
4. Furrow stream size
5. Application period
6. Irrigated area
7. System flow capacity

The furrow grade will depend on the site topography. A grade of 2% is the recommended maximum for straight furrows. Furrows can be oriented diagonally across fields to reduce grades. Contour furrows or corrugations can be used with grades in the range of 2% to 10%.

The furrow spacing depends on the water intake characteristics of the soil. The principal objective in selecting furrow spacing is to make sure that the lateral movement of the water between adjacent furrows will wet the entire root zone before it percolates beyond the root zone. Suggested furrow spacings based on different soil and subsoil conditions are given in Table 8-14.

The length of the furrow should be as long as needed to permit reasonable uniformity of application, because labor requirements and capital costs increase as furrows become shorter. Suggested maximum furrow lengths for different grades, soils, and depths of water applied are given in Table 8-15.

The furrow stream size or application rate is expressed as flow rate per furrow. The optimum stream size is usually determined by trial and adjustment in the field after the system has been installed [6]. Highest application efficiency generally can be achieved by starting the application with the largest stream size that can be safely carried in the furrow. Once the stream has reached the end of the furrow, the application rate can be reduced or cut back to reduce the quantity of runoff that must be handled. As a general rule, it is desirable to have the stream size large enough to reach the end of the furrow within one-fourth of the time required for infiltration, which is equivalent to one-fifth of the total application period.

Supply pumps and transmission systems should be designed to provide the maximum allowable stream size, which is generally limited by erosion considerations when grades are greater than 0.3%. The maximum nonerosive stream size can be estimated from the equation:

Table 8-14. Optimum furrow spacing [7].

Soil condition	Optimum spacing (inches)
Coarse sands--uniform profile	12
Coarse sands--over compact subsoils	18
Fine sands to sandy loams--uniform	24
Fine sands to sandy loams--over more compact subsoils	30
Medium sandy-silt loam--uniform	36
Medium sandy-silt loam--over more compact subsoils	40
Silty clay loam--uniform	48
Very heavy clay soils--uniform	36

Table 8-15. *Suggested maximum lengths (in feet) of cultivated furrows for different* soils, and depths of water to be applied [8].

Furrow grade (%)	Average depth of water applied (inches)											
	Clays				Loams				Sands			
	3	6	9	12	2	4	6	8	2	3	4	5
0.05	3,000	1,300	1,300	1,300	400	900	1,300	1,300	200	300	500	600
0.1	1,100	1,400	1,500	1,600	600	1,100	1,400	1,500	300	400	600	700
0.2	1,200	1,500	1,700	2,000	700	1,200	1,500	1,700	400	600	800	1,000
0.3	1,300	1,600	2,000	2,600	900	1,300	1,600	1,900	500	700	900	1,300
0.5	1,300	1,600	1,800	2,400	900	1,200	1,500	1,700	400	600	800	1,000
1.0	900	1,300	1,600	1,900	800	1,000	1,200	1,500	300	500	700	800
1.5	800	1,100	1,400	1,600	700	900	1,100	1,300	250	400	600	700
2.0	700	900	1,100	1,300	600	800	1,000	1,100	200	300	500	600

$$q_e = 10/G \qquad [8\text{-}22]$$

where q_e = maximum unit stream size, gal/min
G = grade, %

For grades less than 0.3%, the maximum allowable stream size is governed by the flow capacity of the furrow, estimated as follows:

$$q_c = (74)(F_a) \qquad [8\text{-}23]$$

where q_c = furrow flow capacity, gal/min
F_a = cross-sectional area of furrow, ft^2

The application period is the time needed for water to infiltrate to the desired depth plus the time required for the stream to advance to the end of the furrow. The time required for infiltration depends on the water intake characteristics of the furrow. There is no standard method for estimating the furrow intake rate. The recommended approach is to determine furrow intake rates and infiltration times by field trials as described elsewhere [6].

The irrigated area per irrigation depends on the number of applications that can be made per day, which in turn depends on available labor and the application period. The irrigated area may be calculated as follows:

$$A_i = \frac{A_w}{(N_a)(t_d)} \qquad [8\text{-}24]$$

where A_i = irrigated area per irrigation, acre
A_w = field area, acre
N_a = no. of applications per day
t_d = design time between irrigations, day

System flow capacity is a function of the number of furrows in the irrigated area and the furrow stream size. The number of furrows used may be calculated as follows:

$$N_f = \frac{(A_i)(43{,}560)}{(L_f)(S_f)} \qquad [8\text{-}25]$$

where N_f = no. of furrows per irrigated acres
A_i = irrigated area, acre
L_f = furrow length, ft
S_f = furrow spacing, ft

System flow capacity may then be computed as follows:

$$Q = (N_f)(q_e \text{ or } q_c) \qquad [8\text{-}26]$$

where Q = system capacity, gal/min
N_f = no. of furrows per irrigation
q_e, q_c = design maximum furrow stream size, gal/min

Graded Border Distribution

Quasi-rational design procedures have been developed by the SCS for all variations of border distribution systems and are given in the references in Table 8-9.

The design variables for graded border distribution are:

1. Grade of the border strip
2. Width of the border strip
3. Length of the border strip
4. Unit stream size
5. Application period
6. Irrigated area
7. System flow capacity

Graded border distribution can be used on grades up to about 7%, but grades of 2% or less are most common. Terracing of graded borders can be used for grades up to 20%.

The widths of border strips are often selected for compatibility with farm implements, but they also depend to a certain extent upon grade and soil type, which affect the uniformity of distribution across the strip. Guidelines for estimating strip widths are presented in Tables 8-16 and 8-17.

The appropriate length of a border strip depends on the grade, allowable stream size, the depth of water applied, the intake characteristics of the soil, and the configuration of the field. The guidelines presented in Tables 8-16 and 8-17 may be used to make initial estimates of border length.

Table 8-16. Design guidelines for graded border distribution, deep-rooted crops [8].

Soil type and infiltration rate	Grade (%)	Unit flow per 1 ft of strip width (ft^3/sec)	Avg depth of water applied	Border strip width (ft)	Border strip length (ft)
SANDY	0.4-0.6	0.09-0.11	4	30-40	200-300
Infiltration rate of	0.4-0.6	0.09-0.11	4	30-40	200-300
1+ inch/hour	0.6-1.0	0.06-0.09	4	20-30	250
LOAMY SAND	0.2-0.4	0.07-0.11	5	40-100	250-500
Infiltration rate of	0.4-0.6	0.06-0.09	5	25-40	250-500
0.75 to 1 inch/hour	0.6-1.0	0.03-0.06	5	25	250
SANDY LOAM	0.2-0.4	0.06-0.08	6	40-100	300-800
Infiltration rate of	0.4-0.6	0.04-0.07	6	20-40	300-600
0.5 to 0.65 inch/hour	0.6-1.0	0.02-0.04	6	20	300
CLAY LOAM	0.2-0.4	0.03-0.04	7	40-100	600-1,000
Infiltration rate of	0.4-0.6	0.02-0.03	7	20-40	300-600
0.25 to 0.5 inch/hour	0.6-1.0	0.01-0.02	7	20	300
CLAY	0.2-0.3	0.02-0.04	8	40-100	1,200+
Infiltration rate of					
0.10 to 0.25 inch/hour					

Table 8-17. Design guidelines for graded border distribution, shallow-rooted crops [8].

Soil profile	Grade (%)	Unit Flow per 1 acre of strip width (ft^3/sec)	Avg depth of water applied (inches)	Border strip Width (ft)	Border strip Length (ft)
CLAY LOAM	0.15-0.6	0.06-0.08	2-4	15-60	30-600
24 inches deep over	0.6 -1.5	0.04-0.07	2-4	15-20	300-600
permeable subsoil	1.5 -4.0	0.02-0.04	2-4	15-20	300
CLAY	0.15-0.6	0.03-0.04	4-6	15-60	600-1,000
24 inches deep over	0.6 -1.5	0.02-0.03	4-6	15-20	600-1,000
permeable subsoil	1.5 -4.0	0.01-0.02	4-6	15-20	600
LOAM	1.0 -4.0	0.01-4.0	1-3	15-20	300-1,000
6 to 18 inches deep					
over hardpan					

The unit stream size is expressed as a flowrate per unit width of border strip, gal/min·ft or ft^3/sec·ft. The optimum stream size is best determined by field trials as described in elsewhere [6]. The range of stream sizes given in Tables 8-16 and 8-17 for various soil and crop conditions may be used for initial design. Procedures given in the references in Table 8-9 may be used to obtain a more accurate estimate of stream size.

The application period necessary to apply the desired depth of water may be determined by using the following equation:

$$t_a = \frac{(L)(D)}{(96.3)(q_u)} \qquad [8\text{-}27]$$

where t_a = application period, hour
L = border strip length, ft
D = depth of applied water, inch
q_u = unit stream size, gal/min·ft

The irrigated area may be determined using Equation 8-24 in the same manner as described for furrow distribution systems.

System flow capacity depends on the number of strips in the irrigated area, the width of the strips, and the unit stream size. The system flow capacity may be calculated as follows:

$$Q = \frac{(A_i)(q_u)(43{,}560)}{L} \qquad [8\text{-}28]$$

where Q = system flow capacity, gal/min
A_i = irrigated area, acre
L = length of border strip, ft
q_u = unit stream size, gal/min·ft

Materials of Construction

Distribution equipment must be durable and able to function with wastewater that may be high in salinity and suspended solids. Equipment, particularly piping and nozzles, should be corrosion-resistant and free from malfunctions caused by suspended particles and organics in the water supply. Aluminum pipe should be clad inside with a corrosion-resistant lining.

Tailwater Return Systems

Runoff of reclaimed wastewater from the irrigated site is normally prohibited by regulatory agencies. Sprinkler distribution systems should be designed so that runoff of applied water does not occur. Surface systems, however, will almost always produce some runoff or tailwater that must be contained on the site. A typical tailwater return system consists of a sump or reservoir, a pump or pumps, and return pipeline. Guidelines for estimating tailwater volume, the duration of tailwater flow, and suggested maximum design tailwater volume are presented in Table 8-18. Pumps can be any convenient size, but a minimum capacity of 25% of the distribution system flow capacity is recommended [9]. The references in Table 8-9 may be consulted for further details.

Table 8-18. Recommended design factors for tailwater return systems [9].

Class	Rate (inch/hour)	Texture range	Max duration of tailwater flow	Estimated tailwater volume	Suggested max design tailwater volume
			% of application time	% of application volume	% of application volume
Very slow to slow	0.06-0.20	Clay to clay loam	33	15	30
Slow to moderate	0.20-0.60	Clay loam to silt loam	33	25	50
Moderate to moderately rapid	0.60-6.0	Silt loams to sandy loam	75	35	70

Subsurface Drainage Systems

Assessing the need for a subsurface drainage system is discussed, followed by a brief discussion of design considerations.

Need for Subsurface Drainage

Subsurface drainage is necessary to provide a root zone environment conducive to good plant growth. The existence of a high water table (depth to water table less than 10 ft) indicates poor subsurface drainage, so subsurface drains should be installed to drain the soil properly. If no water table or a deep water table exists, then subsurface conditions should be evaluated to determine if drainage problems due to irrigation will occur in the future.

The first thing to consider in this investigation is the soil profile. What is the permeability of the soil down to at least 10 feet? Are there significant differences in permeability due to clay lenses or hard pans? Clay lenses or hard pans can cause a perched water table, which will result in a drainage problem, even though the area-wide depth to the water table is 10 feet or deeper. Changes in soil permeability with depth, such as a light-texture soil overlying a clay soil, can also create drainage problems. If conditions such as described above exist, then drainage problems may also exist and provisions should be made for the installation of a subsurface drainage system.

If an area-wide water table exists, one should evaluate existing flow patterns by installing a network of observation wells and determining the elevation of the water table at each well. This will provide information on the direction of flow, which may in turn help determine the type of drainage system needed. If the data from the observation wells show little change in elevation throughout the area, this may indicate that area-wide subsurface drainage is poor and that the potential exists for drainage problems if the land is irrigated. The flow analysis may also provide data on sources or potential sources of drainage water. If the flow patterns indicate that irrigation of upperlying lands is contributing to the groundwater, a subsurface drainage system may be needed for the lowerlying fields. However, an interceptor drain installed at the upper end of the site in question may be all that is necessary to remove any drainage water.

The location of the site with respect to canals, ditches, rivers, ponds, and other bodies of water should be also considered. Seepage from these bodies of water may contribute substantially to any present or potential drainage problems.

The potential volume of drainage water should also be considered. How much rainfall (and frequency) occurs at the site? What is the leaching fraction needed to control soil salinity?

Drainage System Design Considerations

If the preliminary investigation indicates that drainage problems exist or will occur in the future, then a subsurface drainage system should be installed. However, before any installation, the method of drainage disposal water should be determined. In some areas, deep open-ditch drains are used to convey the drainage water to some disposal point. Water from the subsurface drainage system discharges into these ditches by gravity flow. Where gravity flow is not possible, then a sump is used to collect the drainage water that flows into the sump. A sump pump then discharges the water to the conveyance system.

If no conveyance system designed specifically for subsurface drainage water exists, then a method for disposing of the water must be found. Possible methods include discharging into the irrigation water conveyance system, into streams or channels, recirculating the water back onto the irrigated land, discharging to a marsh, or using evaporation ponds. The limiting factor on discharging drain water into surface water channels (such as rivers, canals, irrigation ditches) is the quality of the drain water. It may be possible to discharge good-quality drain water, provided the necessary discharge permits are obtained. If the drain-water quality is poor and no means exists to discharge the water without adversely affecting quality of water for downstream users, then on-site disposal must be considered. If this is not possible, then sites with better drainage conditions should be considered.

Once it has been determined that subsurface drainage is necessary and that the drainage water can be disposed of properly, the next step is to design a subsurface system that will provide the needed water-table control. This involves selecting the proper depth and spacing of the drains, which in turn will depend on the crop type, soil type, quality of the subsurface water, quality of the irrigation water, and volume of drainage water.

The depth of the water table needed to maintain a good root-zone environment will depend on factors such as crop type, soil type, and quality of subsurface and applied water. Generally, under arid conditions such as the San Joaquin Valley, the water-table depth is controlled to prevent excessive accumulation of salts due to upward flow of saline groundwater into the root zone. The quality of the subsurface water is usually much poorer than that of the applied water. Recommended depths to the water table are listed in Table 8-19. Also, where saline high water tables exist, salt-tolerant crops should be used.

Table 8-19. Recommended depth (in meters) to water table for arid areas [8].

Crop	Fine-textured soil (permeable)	Medium-textured soil	Light-textured soil
Field	0.9	1.2	0.9
Vegetable	0.9	1.1	0.9
Tree	1.4	1.4	1.1

Note: During fallow periods, the water table should be controlled at a depth of 1.4 meters for light- and fine-textured soils and 1.5-1.8 meters for medium-textured soils.

In some areas, however, such as along the central California coast, drainage may be needed only to prevent waterlogging of the soil and to improve trafficability. In other areas, drains are operated only during the winter months when large amounts of rainfall occur. Drainage water in these areas is generally of good quality.

The spacing of the drains required to maintain the desired water table level will depend on the volume of water to be drained, the hydraulic conductivity of the soil, and the elevation difference between the water table at the midpoint between drains and the drain tubing. The hydraulic conductivity is a measure of the ease at which water moves through the soil. Soils such as sand generally have high hydraulic conductivities, while clay soils generally have low conductivities; however, these are not necessarily true for all cases. In any event, it is recommended that measurements of hydraulic conductivity be made at the location in question (see Chapter 4).

The auger-hole test is the most common and easiest method of measuring in-situ hydraulic conductivity. The method consists of augering a hole down to at least the desired depth of the drain (Figure 8-3), allowing the water in the hole to come into equilibrium with the water table and then rapidly emptying the hole. After the hole is emptied, the water level in the hole is measured with time. These data are then plotted as depth to the water in the hole versus time, and the slope of this curve is determined for small times (Figure 8-4). The slope is then used with the following equation:

$$K = -C \times \text{slope of line at small times} \qquad [8\text{-}28]$$

to calculate the hydraulic conductivity. The term C depends on the shape of the auger hole, the depth of the hole below the water table, the depth of water in the hole after the initial emptying, and the location of impermeable or permeable layers with respect to the bottom of the auger hole. Values of C for various conditions are presented in Table 8-20.

An estimate of the volume of water to be drained can be made from an estimate of the volume of deep percolation using the following equation:

$$q = \frac{(P/100)_i}{F} \qquad [8\text{-}29]$$

where q = drainage coefficient (volume of water to be drained in 24 hours)

i = depth volume of applied water

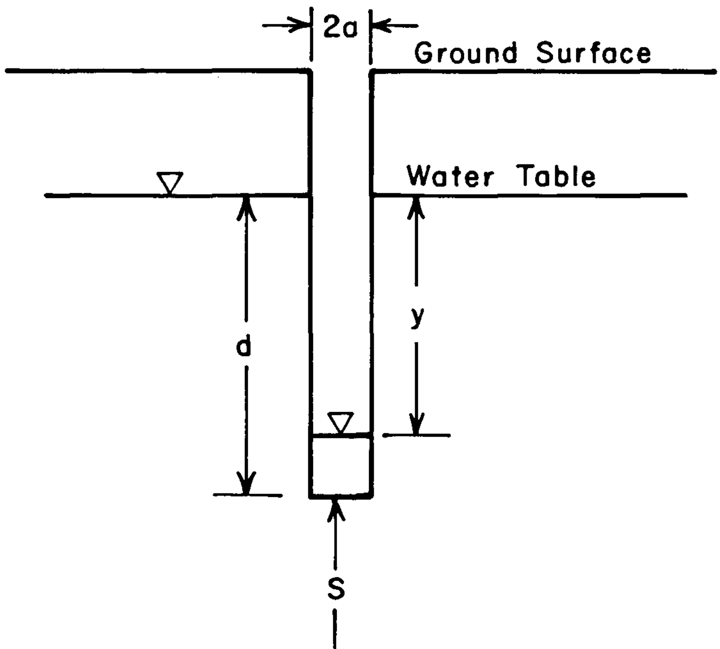

Figure 8-3. Auger-hole test.

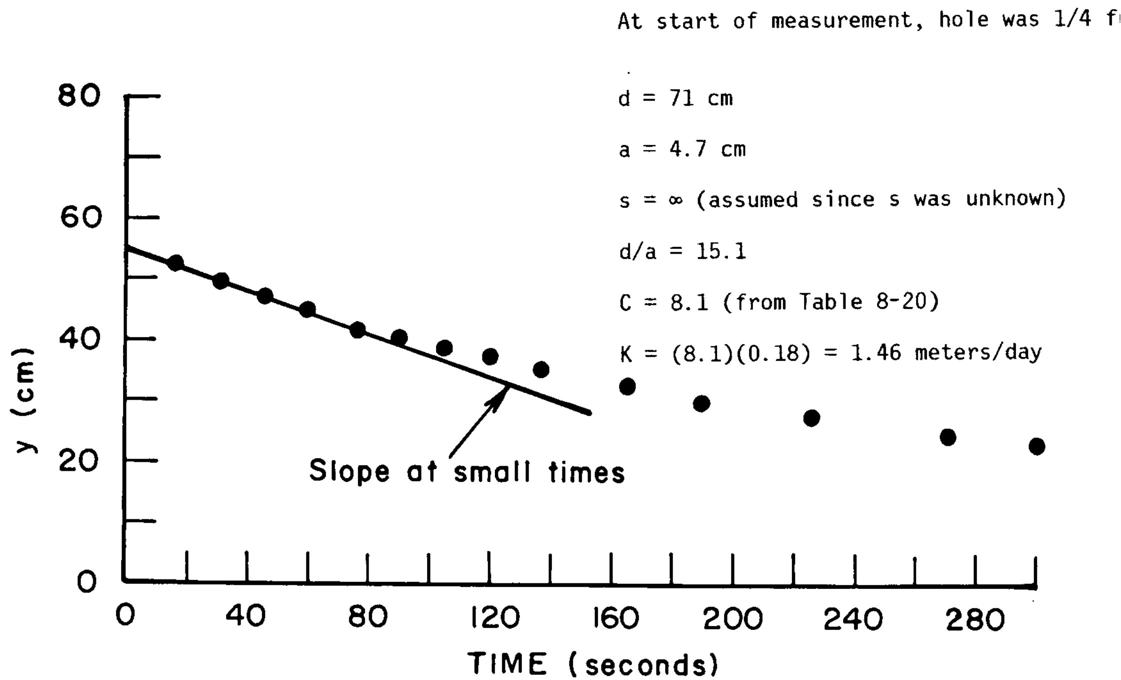

Figure 8-4. Example of auger hole method for measuring hydraulic conductivity.

Table 8-20. Values of C. The rate of rise of water in the auger hole is measured in cm/sec, this value is multiplied by C′ to find the value k in meters/day of the hydraulic conductivity of the soil surrounding the auger hole [21].

d/a		Impermeable barrier at s/d = 0.00	0.05	0.10	0.20	0.50	1.00	2.00	5.00	s/d = ∞ (infinite medium)	Gravel at s/d = 5.00	2.00	1.00	0.50
1.	empty	447.0	423.0	404.0	375.0	323.0	386.0	264.0	255.0	254.0	252.0	241.0	213.0	166.0
	1/4 full	469.0	450.0	434.0	408.0	360.0	324.0	303.0	292.0	291.0	289.0	278.0	248.0	198.0
	1/2 full	555.0	537.0	522.0	497.0	449.0	411.0	386.0	380.0	379.0	377.0	359.0	324.0	264.0
2.	empty	186.0	176.0	167.0	154.0	134.0	123.0	118.0	116.0	115.0	115.0	113.0	106.0	91.0
	1/4 full	196.0	187.0	180.0	168.0	149.0	138.0	133.0	131.0	131.0	130.0	128.0	121.0	106.0
	1/2 full	234.0	225.0	218.0	207.0	188.0	175.0	169.0	167.0	167.0	166.0	164.0	156.0	139.0
5.	empty	51.9	58.6	46.2	52.8	38.7	36.9	36.1		35.8		35.5	34.6	32.4
	1/4 full	54.8	52.0	49.9	46.8	42.8	41.0	40.2		40.0		39.6	38.6	36.3
	1/2 full	66.1	63.4	61.3	58.1	53.9	51.9	51.0		50.7		50.3	49.2	46.6
10.	empty	18.1	16.9	16.1	15.1	14.1	13.6	13.4		13.4		13.3	13.1	12.6
	1/4 full	19.1	18.1	17.4	16.5	15.5	15.0	14.8		14.8		14.7	14.5	14.0
	1/2 full	23.3	22.3	21.5	20.6	19.5	19.0	18.8		18.7		18.6	18.4	17.8
20.	empty	5.91	5.53	5.30	5.06	4.81	4.70	4.66		4.64		4.62	4.58	4.46
	1/4 full	6.27	5.94	5.73	5.50	5.25	5.15	5.10		5.08		5.07	5.02	4.89
	1/2 full	7.76	7.34	7.12	6.88	6.60	6.48	6.43		6.41		6.39	6.34	6.19
50.	empty	1.25	1.18	1.14		1.11	1.07	1.05		1.04			1.03	1.02
	1/4 full	1.33	1.27	1.23	1.20	1.16	1.14			1.13			1.12	1.11
	1/2 full	1.64	1.57	1.54	1.50	1.46	1.44			1.43			1.42	1.39
100.	empty	0.37	0.35	0.34	0.34	0.33	0.32			0.32			0.32	0.31
	1/4 full	0.40	0.38	0.37	0.36	0.35	0.35			0.35			0.34	0.34
	1/2 full	0.49	0.47	0.46	0.45	0.44	0.44			0.44			0.43	0.43

P = Percent of applied water that is deep percolation

F = interval between irrigations

However, in some cases, significant lateral flow of subsurface water can occur from adjacent or upperlying levels. Generally, the volume of lateral flow will be unknown.

Once the hydraulic conductivity, volume of drain water, depth of the water table at the midpoint between the drains, and depth of the drains are known, the spacing can be calculated using an appropriate method. The nomograph [22] shown in Figure 8-5 is commonly used for the San Joaquin Valley and was developed from drainage discharge and water table depth measurements of existing drainage systems. The procedure consists of first calculating the ratio of the drain discharge, q, over the hydraulic conductivity, K (note that the same dimensions must be used for both terms), and then locating q/K along the vertical axis. One then proceeds horizontally until the line representing the desired water table height above the drain, m, is intersected. (The value m is the difference between the depth of the drain and the depth of the water table at the midpoint between drains.) A vertical line is then drawn through the point of intersection down to the horizontal azis. The intersect of the vertical line with the horizontal axis gives the desired spacing. The procedure is illustrated in Figure 8-5. References in Table 8-9 provide more detailed procedures to other design methods.

If significant lateral inflow is believed to occur, then the spacing should be decreased somewhat to adjust for this additional flow. However, this adjustment is done by trial and error. If, after drain systems are installed, the water table depths at the midpoint are not adequate, it may be necessary to install additional drains by splitting the spacing.

Operation Plan

In addition to the construction plans and documents, the design engineer should provide an operation plan for use by the system operator. The plan should contain the following information.

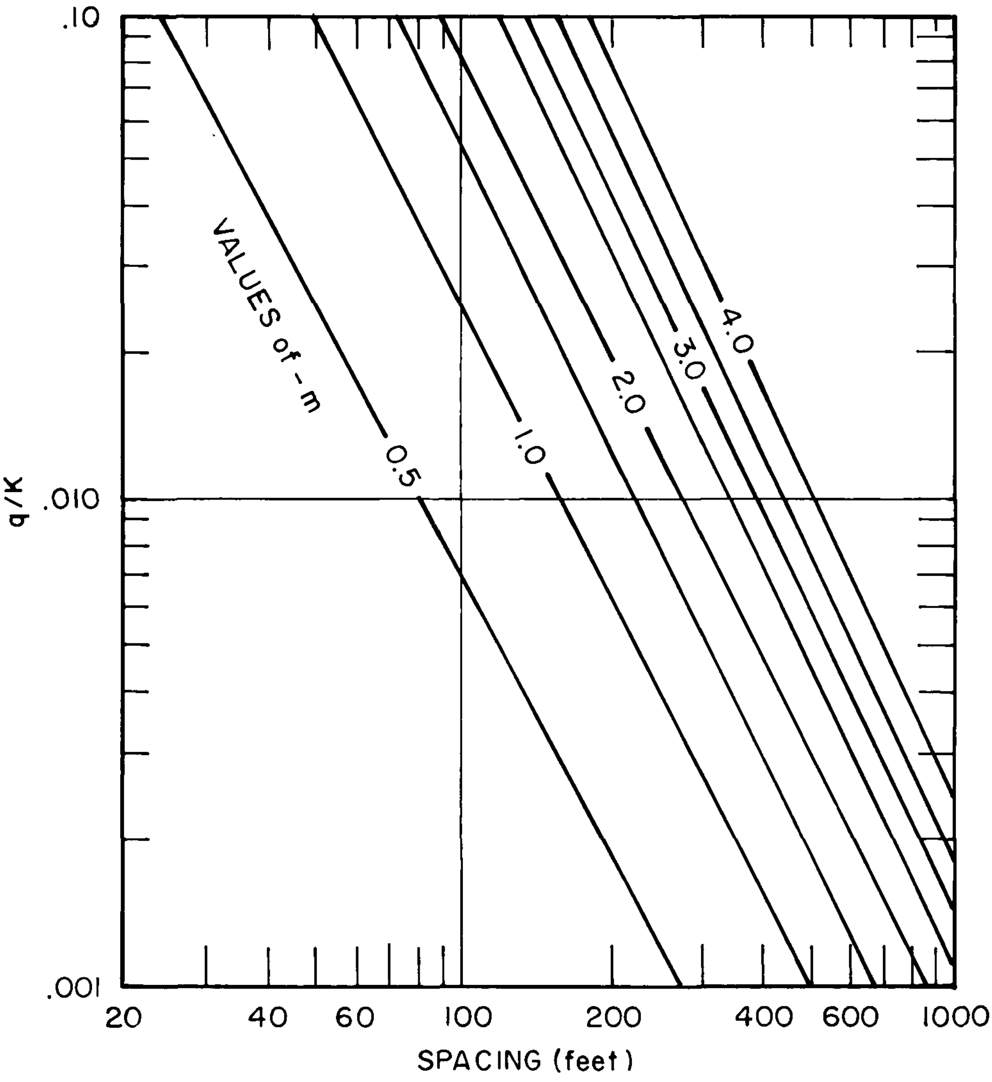

Figure 8-5. Nomograph used for determining drain spacings in the San Joaquin Valley

1. A layout map of the irrigated area showing:
   a. field or plot numbers, area, and crop
   b. irrigation system layout and controls
   c. drainage system layout and controls
   d. other pertinent information
2. Soil profile information showing:
   a. Textural changes with depth
   b. Available water capacity (AWC)
   c. Management-allowed deficiency before irrigation is scheduled (MAD)
3. Crop information:
   a. how to establish the crop
   b. crop rotations if necessary
   c. rooting depth
   d. critical growth periods
4. Irrigation water to be used
   a. source (wastewater or blend)
   b. irrigation-water-quality constituents
   c. flow rates and time available
   d. operating pressure
   e. how to control flow or pressure
5. How to schedule irrigations
6. How to tell when to stop irrigation
7. How many fields can be irrigated at the same time
8. Which fields should be irrigated first, second, etc.
9. Sequence to follow in starting the irrigation system
10. Sequence to follow in stopping the irrigation system
11. Safety checks
12. Maintenance procedures and frequency
13. Monitoring schedule required by regulatory agencies or for crop management
14. As-built plans of the system

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CHAPTER 9

ON-FARM ECONOMICS OF RECLAIMED WASTEWATER IRRIGATION

Charles V. Moore, Kent D. Olson and Miguel A. Mariño

INTRODUCTION

For irrigation with reclaimed wastewater to be a reasonable alternative for municipalities, financial and economic feasibility for farm owners-operators, landowners, and farm tenants must be shown. Financial and economic feasibility are important to both the farmer and the municipality. In the case where a municipality owns the land, the project must be attractive to potential tenants: landowners/farm operators must be better off contracting for the water rather than doing without. But this chapter focuses only on the farmer's view.

In this chapter, we will first briefly describe the supply characteristics of treated wastewater with respect to seasonality of flows (with and without storage), transportation costs, and pricing considerations. Next we will characterize the components making up economic demand for treated wastewater, including monthly evapotranspiration of adoptable crops, alternative application methods, nutrient value of primary and secondary treated wastewater, and salinity problems, and will make some general comments on risk and uncertainty. Finally, we will look at the treatment-disposal system as a whole using a linear programming model of an individual farm to indicate the sensitivity of a profit-maximizing farm operator to variations in the supply-and-demand characteristics and contractual arrangements of reclaimed wastewater.

SUPPLY CHARACTERISTICS OF TREATED WASTEWATER

Seasonal Variations in Wastewater Flows

Seasonal variations in wastewater flows occur in communities with seasonal commercial and industrial activities [1]. The seasonal fluctuation of population, such as students and tourists, also results in an extreme variation in wastewater flows. See Chapter 2 for additional detail on seasonal variation.

Figure 9-1 shows the monthly pattern of inflows to the municipal wastewater treatment plant at Davis, California, a city of approximately 35,000 people with no major water-using industry. The single large food-processing plant in the city has its own treatment facilities, as does the University of California.

Conveyance Systems Costs

The total transportation cost to a reuse site will depend heavily on the distance from the treatment plant and the lift, if any, to move the treated wastewater to an area where soils and topography are conducive to irrigated farming.

Construction costs vary from one geographical area to another as well as within the same area, depending upon the particular construction condition encountered (e.g., open-land versus in-city construction). Construction costs also vary according to the size and material of pipe used, appurtenances, construction depth, pumping requirements, etc. For example, a typical construction cost curve, in 1978 dollars as a function of capacity, is given in Ocanas and Mays [2]. It is based on data collected by Dames and Moore [3] such that:

$$\text{Pipe construction cost (\$/ft)} = 80.0\ Q^{0.461} \qquad [9\text{-}1]$$

in which Q is the design capacity in millions of gallons per day (MGD). Construction bid costs were collected by Dames and Moore [3] for over 500 sanitary sewer pumping stations ranging in capacity from 0.1 MGD (380 m^3/day) to over 100 MGD and with pumping heads from 10 ft to over 100 ft. This survey led to the following cost equation:

$$\text{Pumping station cost (\$/ft of head)} = 1.33 \times 10^5\ Q^{1.08} \qquad [9\text{-}2]$$

in which Q is the design capacity in MGD.

Off-Line Storage

Design factors for the reclaimed wastewater storage capacity required in land application systems include length of the nonapplication season, wastewater flow, precipitation, evaporation, and seepage [4]. Based on climate and weather variations, computer programs have been developed by the U.S. Environmental Protection Agency (EPA) [5] that enable the estimation of storage requirements for all portions of the United States. For example, the average

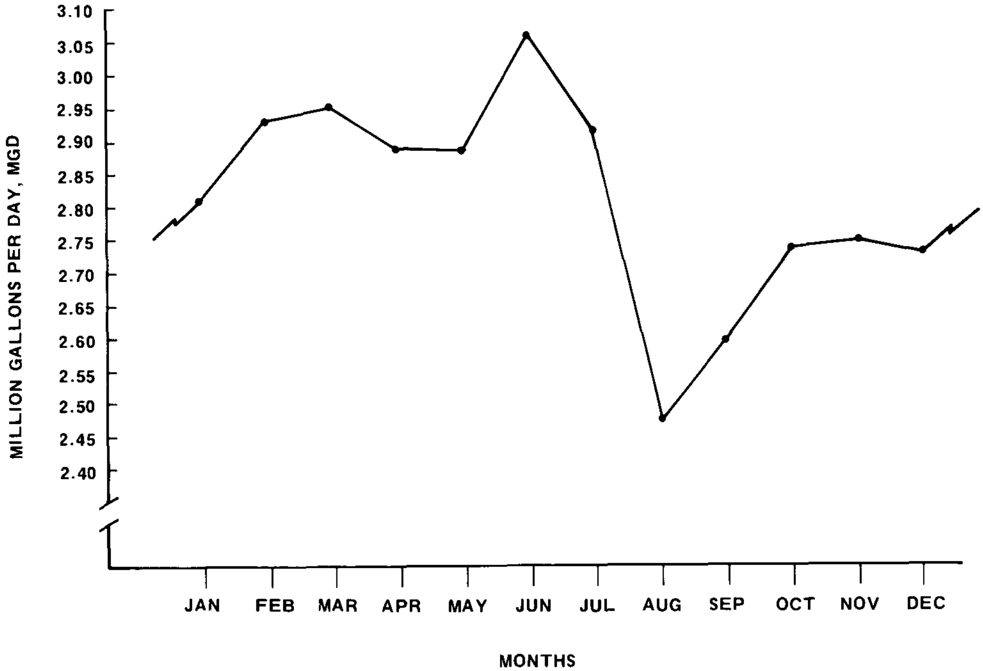

Figure 9-1. Daily inflows by month to the municipal wastewater treatment plant at Davis, California, 1973-81.

number of nonapplication days for which storage would normally be required in Sacramento is about 40 days.

Most agricultural reservoirs are constructed with earth embankments of uniform materials [6]. In California, any reservoir with embankments higher than 6 ft (1.8 m) and a capacity in excess of 50 acre-ft (61,600 m^3) is subject to state regulations on design and construction of dams, and plans must be reviewed and approved by the appropriate agency [7].

Figure 9-2 shows capital and annual costs vs. storage volume. For a storage volume of 1 MG, the capital outlay is expected to be about $5,000 (in 1979 dollars). In addition, one may require reservoir lining and embankment protection. There are significant economies of size in operation and maintenance costs, as indicated in Fig. 9-2b. These costs are based on idealized data: Reed et al. [8] give additional information on data development.

Depending on the contractual arrangements between the municipality and the landowner, the cost of storing wastewater may be paid by the city, by the landowner, or by both. Storage costs can be quite significant and must be taken into account in determining the economic feasibility of utilizing reclaimed wastewater. The importance and impact of off-line storage for farm operators utilizing treated wastewater will be clarified in the discussion on matching supply and demand for water in a later section entitled "Putting It All Together".

Pricing Considerations

The municipalities' objective in pricing reclaimed wastewater would be to minimize the cost of disposing of a fixed quantity of wastewater subject to water quality standards. If these standards for disposal into a water course require tertiary treatment, costs may be minimized by giving away the water to avoid the expense of meeting these stringent standards. However, the demand for irrigation water may be great enough to allow the municipality to recover all treatment, transportation, and storage costs through sales to farm operators.

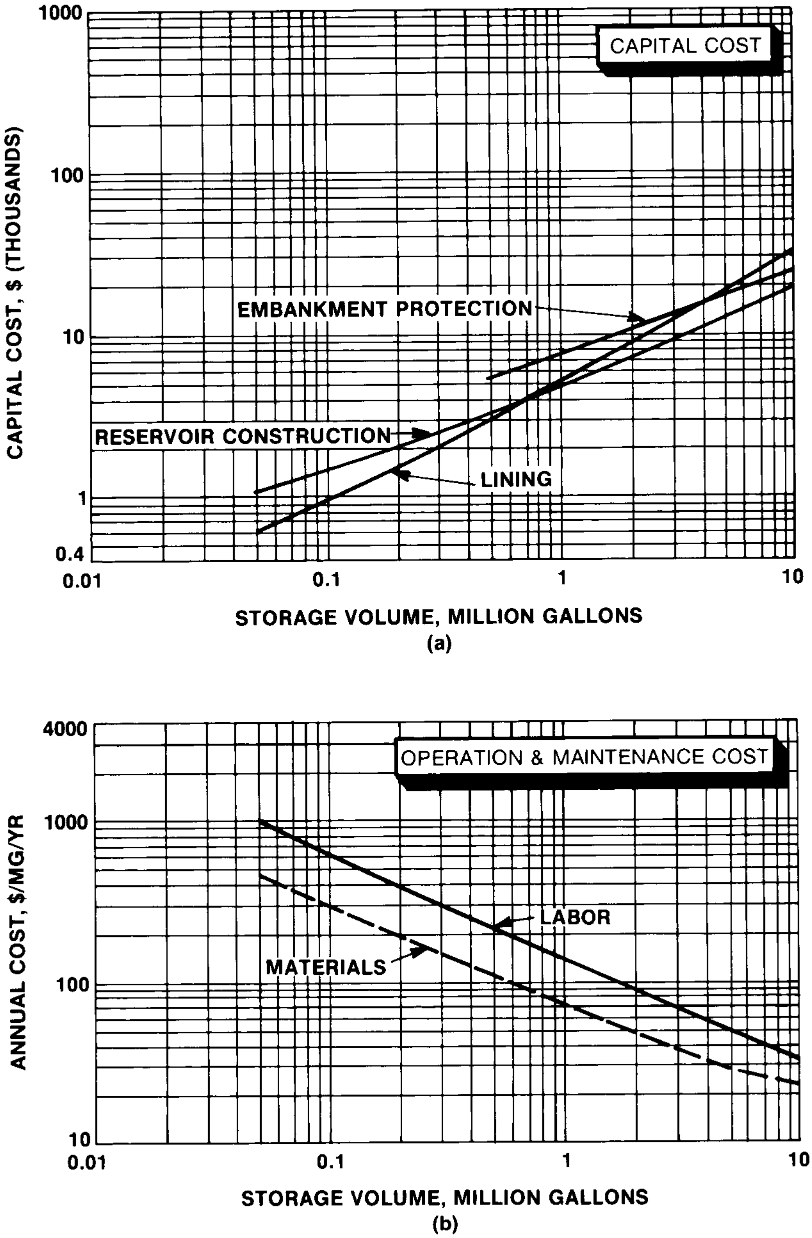

Figure 9-2. Cost curves for storage reservoir in 1979 dollars [8]

Landowners/farm operators, on the other hand, would have profit maximization as their economic goal, and their decision to purchase or accept treated wastewater will be based on the quantity, timing, quality, and cost of treated wastewater.

The final contract price will be negotiated considering all of these variables and factors. If, for example, water-quality standards require that effluent be usable for water contact sports and this level of treatment costs $133 per acre-ft or $0.41 per 1,000 gal ($0.11/m^3$), the municipality would be better off subsidizing the cost of water to farmers up to $133 per acre-ft rather than paying to treat the wastewater. In fact, farm operators may be willing to pay for secondary treated water, thus decreasing the municipality's net cost of treatment.

The order of magnitude of treatment costs for various uses are shown in Table 9-1. These costs (1974 dollars) for water reuse have been adapted from Middleton [9] for 10 MGD (37.8×10^3 m^3/day) treatment systems. (The costs given are examples and do not apply to any specific local situation.)

System Reliability

The Wastewater Reclamation Criteria are contained in Title 22, Division 4, Sections 60301-60357 of the California Administrative Code (see Appendix F) and are discussed in Chapter 10 of this manual. A recent survey on wastewater reclamation facilities was conducted by the California State Department of Health Services in 1977-78 [10]. The survey revealed that 72% (176 out of 243) of the wastewater reclamation plants provided higher treatment than required for the intended use.

DEMAND CHARACTERISTICS OF IRRIGATION WATER

Seasonal and Daily Patterns of Demand and Transportation

Crops need different amounts of water at different seasons of the year. In California, summer months are high-demand months for irrigation water, while winter months have more rainfall and cooler weather. (Year-to-year fluctuations in evapotranspiration (ET) may vary widely from the long-term average, so the quantity of water

Table 9-1. Treatment costs by type of use (1974 dollars) [9].

Water reuse	Capital cost ($1,000)	Total operating cost (cent/1,000 gal)	Dollars per acre-ft
Irrigation	a	a	a
Recreation	9,641	40.7	132
Industrial	8,237	35.6	116
Domestic:			
Nonpotable	6,302	24.3	80
Near potable	12,357	62.2	202

a. Depends on water quality requirements for irrigation.

required for a specific crop will vary also.) The amounts of evaporation and transpiration have been quantified for types of crops and by geographical area. The ET rate varies with the amount of leaf area, temperature, wind, and other climatic conditions. Chapter 5 gives further details on ET data.

ET rates can be used to estimate the demand for water. However, oversupply of water can be just as detrimental as an undersupply. In low-demand months, alternative storage or disposal methods will probably be needed for excess water not required by crops.

This variation in demand may cause a variation in the pricing of water. Water in the summer is worth more, because the demand is greater. Water in the winter is worth less, because farmers may have no need for water--they may even have an oversupply in rainy years. There may be a need to pay farmers for disposal in the low-use months; however, farmers may be willing to pay for reclaimed wastewater in the high-use months. Using farm land for wastewater disposal in the low-use months may preclude the growing of crops in other months if disposal overlaps with planting and/or harvesting periods.

Potentially Adaptable Crops

Depending on the level of treatment by the municipality before delivery to the farm, it is possible to irrigate virtually any crop with reclaimed municipal wastewater. Thus, it is very important for the farm operator to have a clear understanding of reclaimed-wastewater-quality characteristics before contracting for it. For a detailed discussion of water-quality characteristics and their effects on crop selection, further reading in Chapters 2, 3, and 10 is recommended.

Limitations Due to Health Concerns

Reclaimed wastewater that has been oxidized, coagulated, clarified, filtered, and disinfected, can be used to irrigate a wide variety of crops. If the coliform count is below 2.2/100 mL, tertiary-treated wastewater can be used to irrigate food and vegetable crops, even under sprinkler irrigation. In other words, it can be used for any purpose that a farm operator would normally use irrigation water supplied from underground or district water sources. However, if this water is priced at the cost to the municipality, it can be expected to be relatively expensive.

Use of secondary treated effluent somewhat limits the types of crops that can be grown. If the effluent is oxidized and disinfected and the coliform count is not below 2.2/100 mL, the secondary treated wastewater can be applied to irrigated pasture for dairy animals but not to food crops.

Primary effluent use is limited to nonfood crops such as forages, fiber, and seed crops; however, it may be used in orchards and vineyards if the treated wastewater is applied by surface-irrigation methods. Additional detailed treatment requirements can be found in the Wastewater Reclamation Criteria, California Administrative Code Title 22, Division 4, Environmental Health, 1978 (see Appendix F) and also are discussed in Chapter 10.

Limitations Due to Climate

Climatic conditions affect the demand for irrigation water (and thus reclaimed wastewater) in two ways. First, short-growing-season areas limit the choice of crops available to the farm operator. In most cases, high-elevation areas will be limited to irrigated pasture, forages, and winter grain crops. The shorter growing season also implies lower total plant evapotranspiration and thus lower total water use per acre.

Second, even for areas with longer growing seasons (225 days or more), the demand for irrigation water can vary owing to changes in average daily temperature and wind speed. Thus, a forage crop grown in the desert area of southern California will consume significantly more water both in the peak months and in seasonal totals than the same crop grown in the Sacramento Valley. All other things being equal, the additional yield due to the longer growing season in southern California would enhance that region's ability to pay for water over that of an area with a shorter growing season.

Limitations Due to Soils

Information presented in Chapter 4 of this manual provides details on the hydraulic conductivity of soils. In general, the concentration of dissolved solids in treated wastewater will be higher, perhaps by 300 mg/L, than that of the municipal supply (see also Chapter 2). Drainage of a specific soil, either natural or artificial, will affect the ability of salts to move through the root zone. Low-salt tolerant crops will be difficult to germinate and will fail to produce satisfactory yields on these soils without careful irrigation management. In some cases, production may be economically infeasible.

Market Considerations

Most field and forage crops are grown widely throughout the United States, and thus access to a market is no problem. However, for many of California's specialty crops, a production or marketing contract is almost a necessity. The financial risk of not having a "home" for perishable crops at harvest time may be too great for some farms. Processing tomatoes and sugar beets, although grown widely in California, require a production contract with a processor. Thus because of contract necessity, a grower may not be able to change the crop mix quickly to use treated wastewater for irrigation. That is, the production, harvesting, and marketing schedules may not be flexible enough to allow for irrigation (i.e., disposal) of municipal wastewater during all periods.

Less perishable crops, such as wheat, pasture, or corn, may be more suitable for wastewater irrigation, because the market usually does not require marketing contracts and the grower has more flexiblity. Thus, these crops can adjust to the schedule of wastewater irrigation more readily than perishable commodities.

Distribution and Application Methods

Irrigation distribution systems generally fall into two broad categories: surface and sprinkler. A large number of combinations exist within these categories. In choosing the least-cost combination from the wide range of technologies available, the farm operator must have a knowledge of labor wage rates, water costs, interest rates, and power charges over time as well as of the soils, adaptable crops, and climatic conditions for the disposal-site farm.

This manual cannot cover all of the possible irrigation methods but can suggest broad guidelines for the planner. As the cost of water supplies increases in relation to wages and interest rates, additional capital can be invested profitably in water-conserving technologies. For example, under surface irrigation, as water costs increase, funds could be invested in reducing water losses by using pipelines, tailwater systems, laser leveling, and shorter lengths of runs.

Sprinkler systems tend to have similar irrigation application efficiencies so that system selection is heavily weighted toward those that reduce irrigation labor and have lower amortization and operating cost. Topography may dictate that sprinklers provide the only feasible method of irrigating a certain parcel. However, in deciding to irrigate or not to irrigate, the following factors should be kept in mind:

1. One pound of pressure per square inch (6.9 kPa) at the nozzle is equivalent to 2.31 ft (0.704 m) of head. Thus a 60-lb/inch^2 sprinkler is equivalent to 138.6 ft of lift. A 70-lb/inch^2 requirement would be equivalent to 161.7 feet of head.
2. In 1982, the electrical energy cost for pumping in California was about \$0.11 to \$0.12 per acre-ft per ft of lift. Thus, the cost of pressurizing a sprinkler system would range from \$15.25 to \$16.63 per acre-ft (\$12.16 to \$13.38/1000 m^3). These costs are projected to increase from 2% to 3% faster than the general inflation rate in the next few years.
3. The benefits of water conservation need to be evaluated as well as the costs of obtaining those benefits.

In choosing between surface irrigation methods and sprinklers, all other things being equal, significantly lower irrigation efficiencies and higher labor costs can be tolerated for surface irrigation before increasing water cost causes sprinklers to become cost-effective. A least-cost irrigation system should be selected only after considering all of these factors and the unique characteristics of the fields to be irrigated.

Alternative Irrigation Methods

Although the use of drip irrigation (with fresh water) is increasing, this section will not discuss drip irrigation with treated wastewater, because such experience in California is extremely limited.

Sprinkler System

The decision to use sprinkler or surface methods for applying irrigation water is not simple or trivial. Except for the requirements due to health concerns discussed earlier, the choice should be made on the same basis as if normal water sources were involved.

Sprinklers may be indicated when topography or nonuniform soil types make surface irrigation impossible. Other advantages of sprinklers might include better salt management, more uniform, light irrigations, and temperature and humidity control. Disadvantages might include high initial investment, amortization, and operating costs. With the rapid increase in energy costs, serious consideration should be given to the power costs of pressurizing and operating a sprinkler system in the future. In addition, the irrigator must consider the fixed costs of interest and depreciation along with repair and maintenance costs.

There appears to be no unique advantages with respect to type of sprinkler system, i.e., hand move, wheel roll, solid set, center pivot, etc., when utilizing treated wastewater. Thus, the choice of system must be based on economic and other considerations. However, care must be taken to position sprinklers or use shields so that wastewater does not drift onto adjacent property.

Surface System

Except for the limitations due to health concerns discussed earlier, use of treated wastewater for irrigation should have little effect on the choice of a surface distribution system. The most important consideration is to select the most cost-effective distribution system, given the price of water, labor wage rate, and interest rates. The higher the price (cost) of treated wastewater at the farm headgate, the greater the financial feasibility of investing in water-conserving devices and practices such as pipelines, gated pipe, laser leveling, and shortened length of runs.

Return Flow Systems

Regardless of whether a sprinkler or surface system is selected, a return flow or tailwater recovery system may be required under certain conditions. County health departments and/or regional water quality control boards may prohibit tailwater from leaving the field to enter drains or water courses. This prohibition may be imposed when primary or secondary treated wastewater is used, especially when excess water is applied over and above crop consumptive use in order to "dispose" of surplus water. If the farm headgate cost of treated wastewater is relatively high, a tailwater recovery system may be a cost-effective water conservation practice.

Value of Nutrients in Treated Wastewater

Plant nutrients are subject to the laws of diminishing returns just like any other variable input. For example, Figure 9-3 shows the results of a Sonoma County field trial comparing secondary treated wastewater containing 46 lb of N, 87 lb of P, and 43 lb of K per acre-ft (16.9 mg/L N, 32.0 mg/L P, 15.8 mg/L K) against fresh water from the municipal water supply. Diminishing returns to nitrogen are shown both for dry-weight and fresh-weight yields of the corn silage.

Placing a value on plant nutrients in treated wastewater is more difficult. However, some things can be inferred from data such as these. First, in this experiment, little additional production is generated after 50 lb of additional N is applied per acre, and after application of 75 lb N per acre, total yield starts to decline. Thus, if the nitrogen were free, a farm operator could profitably apply 75 lb of N per acre. However, if the nutrients were assigned their market value if purchased as commercial fertilizer, the optimum level of application would be less than 75 lb per acre.

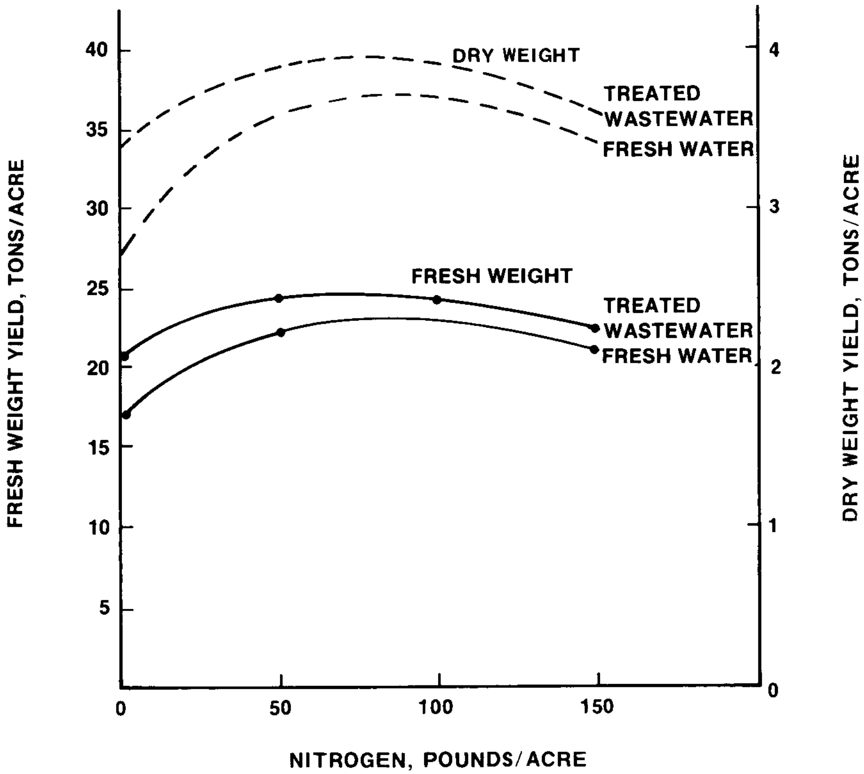

Figure 9-3. Corn silage yield response to nitrogen in Sonoma County, California, 1975.

In general, depending on the crop under consideration and the shape of the dose-yield response curve, the value of the nutrient content increases up to where the nutrient exceeds the level that causes yields to decline; its value then becomes zero or negative. That is, if the wastewater in the above example contains 46 lb of N per acre-ft and 3 acre-ft (3700 m^3) are applied, then the value of N in the last acre-ft would be zero or even negative. If for example, a primary treated wastewater contained approximately 100 lb of N per acre-ft, much of the nutrient content could be wasted if not blended with water supplies from fresh water sources. If a treated wastewater contained only 50 lb of N per acre-ft it would more nearly match nutrient supply with plant requirements, except on certain crops, such as sugar beets and processing tomatoes, where timing of nutrient availability is somewhat more critical.

An alternative method of valuing nutrients is the market approach. If farm managers choose not to use reclaimed wastewater, then plant nutrients must be purchased from the market. Table 9-2 provides prices paid by farmers per pound of actual nutrient as of March 15, 1981. Thus, for example, if a source of reclaimed municipal wastewater contained 0.23 lb of N per 1,000 gal (81.2 lb/acre-ft or 30 mg/L) the water would have a market equivalent of $12.83 per acre-ft in terms of the alternative cost of purchasing anhydrous ammonia. However, if the crop cannot utilize all of the nutrients, the unused portion has a zero value.

Salts in Reclaimed Wastewater

The salts in municipal wastewater may cause more water to be required to leach any salts that accumulate in the soil. The leaching fraction (LF) is the fraction of the total amount of applied water that drains below the root zone. The method of calculating the required LF is discussed in Chapter 7. If the water is very saline or the crop is salt-sensitive, the required leaching fraction may be fairly high, thus increasing the cost of irrigation substantially. For example, if the LF must be increased from 0.10 to 0.25, the energy cost of sprinkling will increase 20% [=(.25-.10)/(1-.25)].

Table 9-2. Prices paid by farmers for actual plant nutrient [11].

Fertilizer	Analysis (%)	Price per pound of nutrient N or P_2O_5 ($)
Nitrogen		
Ammonium sulfate	20	0.375
Ammonium nitrate	33	0.315
Urea	45	0.282
Anhydrous ammonia	83	0.171
32% Nitrogen solution	32	0.303
Phosphorus		
Superphosphate	20	0.340
Triple superphosphate	45	0.296

In areas of high winter rainfall or where wastewater is blended with higher-quality water sources, leaching requirements will be reduced. Some areas may have groundwater that is saltier than the wastewater; using wastewater would reduce the required leaching over that required if the groundwater was used for irrigation.

The long-term accumulation of salts in the soil can lead to a decrease in the choice of crops to be grown. Chapters 3 and 7 discuss the sensitivity of crops to salt in more detail. Most fruit, nut, and vegetable crops and some field and forage crops are particularly sensitive to salt. A farmer will lose the ability to grow these high-value crops if salt builds up over time. Also, yields will decline for the remaining potential crops.

If the choice of crops decreases and the yield decreases because of salt buildup, the farmer will experience a decline in annual income and a loss in asset value, and the value of the land for agricultural use will decline.

The Effect of Risk and Uncertainty

The choice of whether to use wastewater for irrigation involves risk and uncertainty. Is there a need for a back-up water supply? What are the effects on landowner-tenant agreements? Does variation in crop price and yield affect a farmer's decision? Although risk and uncertainty can be positive in the sense of greater profits, managers usually are more concerned with "downside risk" (i.e., the risk of failure). This section discusses the effects of wastewater utilization on downside risk.

Depending on the reliability of wastewater treatment systems, a farmer may feel the need for a back-up supply of water. The supply of wastewater may or may not be constant. If the supply of wastewater is not constant, the farmer will need another supply of water to cover the needs during periods of wastewater shortfall. Even if the supply is constant, the farmer may need to have reserve well and pump capacity to meet the ET requirements for unpredictable periods of interruption of reclaimed wastewater supply. In either case, the value of the reclaimed wastewater is reduced because of the cost of having a back-up source. Even if the farmer does not have a back-up source, the value of the wastewater is reduced because of the potential loss in income due to plants being put under stress. Stress may occur as a result of the interruption of supply and/or a nonconstant supply of reclaimed wastewater.

By the same reasoning, too much water reduces the value of wastewater. If the contract requires the farmer to dispose of all water from the treatment plant, farm productivity may be negative in some months or on some fields.

The final agreement between landowner and tenant depends upon several factors. An important factor is the amount of risk that is shared between the two parties. This has an indirect effect on the potential use of reclaimed wastewater. With cash rent, the landowner receives a fixed, known income from the land, and the tenant has a considerable amount of freedom in crop selection and how the land is farmed. With a crop-share lease, the landowner receives a larger share of the expected income in return for being willing to share in any loss that may occur. Because the landowner has some uncertainty about his/her income, the landowner will usually participate in more management decisions. Usually the landowner will press for those crops that give the largest return to land, whereas the tenant will press for those crops that give the largest return to his/her management, labor, and capital. These "votes" will not always be for the same crops. The landowner's desires usually limit the crop choices for the tenant. This limiting of choice may reduce the tenant's ability to adapt to the supply and characteristics of reclaimed wastewater for irrigation. In the case where the land is owned by the municipality and not a profit-maximizing landlord, a different set of objectives and constraints will have to be reconciled. For instance, the municipality may have the disposal of all treated wastewater as a primary goal. These conflicts are explored further in the next section.

A very large portion of risk and uncertainty is the variability of crop prices and yields. This variability affects the expected return of different crops. A farmer chooses a crop based in part on the expected income of that crop, the variation in the expected income, and the farmer's ability and willingness to manage that variation. This decision process affects the use of wastewater by potentially removing from consideration a crop or crops that may be useful in adapting to wastewater irrigation. The effect of income variations varies with individual farmers; thus no generalities can be drawn, except that this may restrict the potential adoption of wastewater for irrigation.

PUTTING IT ALL TOGETHER

Linear programming (LP) is a mathematical technique for optimizing an objective by selecting activities or options (crops, livestock, feeds, for example) which compete for limited resources (land, capital, time, for example) or meet other constraints (nutrient requirements, for example). One major use of linear programming in agriculture is maximizing profits by selecting the optimal mix of crops with land, capital, machinery, and time as limited resources.

Linear programming can assist in making decisions for efficient resource allocation among activities and options. LP allows for the simultaneous consideration of many constraints. LP allows the user to answer many "What if..." questions in a quick, orderly fashion.

Linear programming is used to illustrate the trade-offs involved in utilizing reclaimed wastewater in agriculture production. An example of using LP to evaluate the choice of using wastewater is applied to a typical farm in Yolo County, Calif., and the municipal wastewater flow from the city of Davis. The daily flows of Davis wastewater are given in Figure 9-1. Average annual inflow is 1,016 million gallons, and the nitrogen level in the primary effluent is 31.656 mg/L (0.264 lb/1000 gal). These data do not include wastewater from the University of California at Davis or the wastewater from the Hunt-Wesson canning plant. Wastewater from these latter two sources are treated by their own facilities.

A Description of the Model

The LP model maximizes income by choosing crops that allow the constraints to be met. The potential crops are selected on the basis of physical feasibility--in Yolo County in this example. The price, yield, and cost information is included in Table 9-3. The options of

Table 9-3. Prices, yields, costs, and other parameters used in the LP model.

	Wheat	Barley	Corn	Alfalfa	Irrigated pasture	Sugar beets	Tomatoes
Price, $	7	6	7	80	100	25	56.5
Yield per acre	55	50	90	7	1	28	25
Units	cwt	cwt	cwt	ton	acre	ton	ton
Variable cost excluding water and nitrogen costs	91.48	76.57	227.55	176.82	8.6	579.49	670.16
Return over Adj. Var. Costs	293.52	223.43	402.45	383.18	91.4	120.51	742.34
Water Requirements: (1000 gallons/acre)							
January	0	0	0	0	0	0	0
February	13	13	0	1	0	0	0
March	105	105	0	72	72	0	0
April	203	203	0	158	162	74	28
May	277	277	47	231	235	256	98
June	189	189	197	293	297	352	293
July	0	0	389	322	330	389	384
August	0	0	330	275	284	344	263
September	0	0	173	211	215	240	0
October	0	0	0	130	130	143	0
November	0	0	0	35	30	0	0
December	0	0	0	0	0	0	0
Nitrogen required: (lbs, @ $.20/lb)	80	80	200	0	200	125	100

pumping fresh water or using reclaimed wastewater are included. The supply of wastewater is determined for each month. There is some nitrogen available in wastewater; if the crop's need is not met from wastewater, nitrogen can be purchased.

Several cases are evaluated to analyze different conditions that may occur on farms. The changes involve whether the farm has a limited or unlimited acreage, whether the reclaimed wastewater may be blended with fresh water, whether primary or secondary effluent is used, whether all the wastewater must be used on the farm, and at what price of reclaimed wastewater the farmer chooses not to use wastewater. The cases are defined below:

Case I. Maximum size is 350 acres. Primary effluent is used, and blending with fresh water (at $16.00/acre-ft or $0.49/1,000 gal) is allowed. This includes the more likely situation where the total supply of effluent does not need to be used on the farm. No off-line storage is allowed.

Case II. Acreage is unlimited. Only primary effluent is available; blending with fresh water is not allowed. The total supply of effluent does not need to be used on the farm. No off-line storage is allowed.

Case III. Maximum size is 350 acres. Secondary effluent is used, and blending with fresh water is allowed. The total supply of effluent does not need to be used on the farm.

Case IV. Acreage is unlimited. Only secondary effluent is available; blending with fresh water is not allowed. The total supply of effluent must be used on the farm. No off-line storage is allowed.

The results of these cases are reported in the following section.

Summary of Results

Table 9-4 summarizes the results of the LP models, excluding Case IV. Overall, we note that no case uses all available effluent. The crops do not need to be irrigated in winter, and they need less

Table 9-4. Summary of crop acreages, water use and surplus, and nitrogen oversupply in all cases.

Item	Case I		Case II		Case III	
Effluent price range ($ per 1,000 gal)	.01-.02	.025-.045	.01-.03	.01-.02	.025-.035	.04-.045
Crop acreages						
Wheat	0	0	173	0	0	0
Corn	138	245	111	204	216	238
Alfalfa	107	0	0	41	29	7
Tomatoes	105	105	122	105	105	105
Totals	350	350	406	350	350	350
Reclaimed wastewater (1,000 gal)[a]						
Used	390,219	313,609	393,086	342,878	334,299	318,584
Oversupply	626,291	702,901	623,424	673,632	682,211	697,926
Fresh-water use (1,000 gal)	63,497	76,512	0	71,539	72,996	75,667
Nitrogen oversupply (lb/acre)						
Wheat	0	0	205	0	0	0
Corn	137	138	137	24	24	24
Alfalfa	455	0	0	216	216	216
Tomatoes	89	89	248	39	39	39

a. To convert to acre-ft, divide values (in 1,000 gal) by 325.85

water during the early and late part of the growing season. The models do not allow off-line storage; if this were possible, the farm may be able to better utilize the entire wastewater supply. The two main crops chosen are corn and tomatoes; wheat and alfalfa are chosen as conditions and prices vary.

Case I. 350-acre farm, primary effluent, blending with fresh water is allowed but no storage is allowed.

The price for effluent is varied from \$.01/1,000 gal (\$3.25/acre-ft) to \$.045/1,000 gal (\$14.55/acre-ft) in \$.005 increments. The cropping pattern changes only once as the price increases. For \$.01 to \$.02 per 1,000 gal of effluent, the optimum crop mix consists of 138 acres of corn, 107 acres of alfalfa, and 105 acres of tomatoes. For \$.025 through \$.045 per 1,000 gal, the optimum mix is 245 acres of corn and 105 acres of tomatoes. The 350 acres are fully utilized with all prices.

The use of primary effluent decreases by 19.6% when the price reaches \$.025 per 1,000 gal--from 1,198 acre-ft to 962 acre-ft (3.42 acre-ft/acre to 2.75 acre-ft/acre). This occurs at the same water cost where the cropping pattern changes. The unused primary effluent increases at this point--from 1,192 acre-ft to 2,157 acre-ft. The use of fresh water increases from 194 acre-ft to 234 acre-ft.

Surplus and non-utilized nitrogen above the required amount is 137 lbs N/acre-ft for corn, 455 lbs N/acre for alfalfa, and 89 lbs N/acre for tomatoes. As expected, farm gross receipts minus variable expenses declined from \$114,732 to \$102,943 as the price of primary effluent increased.

Overall water use is not very sensitive to changes in the price of water (Table 9-5).

Case II. Unlimited acreage, only primary effluent available, no fresh water allowed, and no storage is allowed.

Varying the effluent price results in no change in the cropping pattern. Fourteen different prices ranging from \$.01/1,000 gal (\$3.25/acre-ft) to \$.30/1,000 gal (\$97.74/acre-ft) are tried. The optimum cropping pattern consists of 173 acres of wheat, 111 acres of

Table 9-5. Monthly water use (1,000 gal) and surplus in Case I--primary effluent price range.

Month	$.01 to $.02 per 1,000 gal[a]			$.025 to $.045 per 1,000 gal		
	Primary effluent		Fresh-water	Primary effluent		Fresh-water
	Use	Surplus	use	Use	Surplus	use
January	0	82,490	0	0	82,490	0
February	96	78,994	0	0	79,090	0
March	7,719	83,731	0	0	91,450	0
April	19,886	66,764	0	2,948	83,702	0
May	41,587	47,983	0	21,830	67,740	0
June	89,351	1,049	0	79,019	11,381	0
July	90,160	0	38,206	90,160	0	45,384
August	77,250	0	25,291	77,250	0	31,128
September	46,429	31,421	0	42,402	35,448	0
October	14,014	70,806	0	0	84,820	0
November	3,727	78,603	0	0	82,330	0
December	0	84,450	0	0	84,450	0
Total	390,219	626,291	63,497	313,609	702,901	76,512

a. To convert to acre-ft, divide values (in 1,000 gal) by 325.85

corn, and 122 acres of tomatoes for a total of 406 acres. Gross receipts minus variable costs ranged from $118,671 to $4,677 as the water cost increased.

Nitrogen above the required amounts is 205 lb N/acre for wheat, 137 lb N/acre for corn, and 228 lb N/acre for tomatoes. The total amount of primary effluent used at each price is a constant 1,206 acre-ft, leaving 1,913 acre-ft unused. Monthly water use is shown in Table 9-6.

Comparing this with Case I (where blending was allowed and included a maximum acreage of 350 acres), we observe a shift away from alfalfa hay to wheat. This causes a lower net income per acre, since wheat returns are lower than those for alfalfa. At an effluent price of $.01/1,000 gal ($3.25/ac-ft), gross receipts minus variable expenses of $114,723 are generated for 350 acres in Case I, or $328/acre, and $118,671 on the 406 acres in Case II, or $292/acre. Thus, expanding the land area to utilize all or nearly all of the effluent without the benefit of storage actually reduces net farm income per acre by $36 per acre.

Case III. 350-acre farm, secondary effluent, blending with fresh water is possible, but no storage is allowed.

Water price is varied from $.01/1,000 gal ($3.25/acre-ft) to $.045/1,000 gal ($14.66/acre-ft) in $.005 increments. The cropping pattern changes twice (though only slightly) as the price increases. For an effluent cost of $.01 to $.02 per 1,000/gal, 204 acres of corn, 41 acres of alfalfa, and 105 acres of tomatoes is the optimum crop mix. From $.025 to $.035, the optimum mix is 216 acres of corn, 29 acres of alfalfa, and 105 acres of tomatoes. Prices of $.04 and $.045 result in 238 acres of corn, 7 acres of alfalfa, and 105 acres of tomatoes as the optimum mix. The 350 acres are fully utilized at each price.

The quantity of effluent used decreases at prices of $0.25/1,000 gal ($81.25/acre-ft) and $.04/1000 gal ($13.05/acre-ft) from its original 1,052 acre-ft to 1,025 acre-ft and then to 977 acre-ft, for a total decrease of 7%. Thus, as the price of reclaimed wastewater

Table 9-6. Monthly water use and surplus (1,000 gal)[a] in Case II - Primary effluent price range.

Month	$.01 to $.30 per 1,000 gallons		
	Primary effluent		Fresh water
	Use	Surplus	Use
January	0	82,490	0
February	2,320	76,770	0
March	18,231	73,219	0
April	38,683	47,967	0
May	65,215	24,355	0
June	90,400	0	0
July	90,160	0	0
August	68,798	8,452	0
September	19,279	58,571	0
October	0	84,820	0
November	0	82,330	0
December	0	84,450	0
Total	393,086	623,424	0

a. To convert to acre-ft, divide values (in 1,000 gal) by 325.85

increases, there is a shift away from reclaimed wastewater to fresh water and a small shift in the cropping pattern. The nitrogen supply above the required levels is 24 lbs N/acre of corn, 216 lb N/acre of alfalfa, and 39 lb N/acre tomatoes. Monthly water use is shown in Table 9-7.

Major differences in cropping patterns are observed between this case (Case III) and Case I (using primary effluent instead of secondary). Under Case I, the optimum plan includes the same crops -- corn, alfalfa, and tomatoes--when the price of the primary effluent is between \$.01 and \$.02/1,000 gal but utilizes different acreages. In Case I, there are 138 acres of corn and 107 acres of alfalfa, but in Case III, over 200 acres of corn and less than 45 acres of alfalfa are planted. It appears that the shift in the crop mix is influenced, in part, by the economical supply of plant nutrients in the primary effluent.

Case I and Case III are similar in that when the price of the effluent increases (whether it is primary or secondary), there is a shift away from alfalfa to corn production.

Case IV is not reported in detail. Case IV is similar to Case III except that the farm acreage in Case IV is unlimited. Although the farm is unlimited in size, it is required to use all available effluent; the farm is physically unable to do this. This is due to two reasons. First, there are not many situations in California requiring irrigation water in December or January. Second, with no other water available except reclaimed wastewater a farm cannot balance the seasonal inequities in supply and demand. Off-line storage and/or land for disposal may enable the farm to take all the treated effluent, but both options will decrease farm income.

In this section, we have shown how a farm would optimize the use of available wastewater. Although these results cannot be applied to other geographical areas, they do show that a farm cannot be expected to take all wastewater without major managerial and operational changes. Over the range of prices considered, the results also show that a farmer would choose to use wastewater at the farm. These optimization models did not evaluate the construction of a distribution system from a treatment plant to a farm field.

Table 9-7. Monthly water use and surplus in Case III--Primary effluent price range.

Month	\$.01 to \$.02 per 1,000 gal[a]			\$.025 to \$.035 per 1,000 gal			\$.04 to \$0.45 per 1,000 gal		
	Primary effluent		Fresh-water	Primary effluent		Fresh-water	Primary effluent		Fresh-water
	Use	Surplus	use	Use	Surplus	use	Use	Surplus	use
January	0	82,490	0	0	82,490	0	0	82,490	0
February	37	79,053	0	26	79,064	0	6	79,084	0
March	2,949	88,501	0	2,084	89,366	0	501	90,949	0
April	9,419	77,231	0	7,523	79,127	0	4,048	82,602	0
May	29,378	60,192	0	27,166	62,404	0	23,113	66,457	0
June	82,966	7,434	0	81,809	8,591	0	79,690	10,710	0
July	90,160	0	42,641	90,160	0	43,445	90,160	0	44,918
August	77,250	0	28,898	77,250	0	29,551	77,250	0	30,749
September	43,941								
October	5,354	79,466	0	3,784	81,036	0	910	83,910	0
November	1,424	80,906	0	1,007	81,450	0	242	82,088	0
December	0	84,450	0	0	84,450	0	0	84,450	0
Total	342,878	673,632	71,539	334,299	682,211	72,996	318,584	697,926	75,667

a. To convert to acre-ft, divide values (in 1,000 gal) by 325.85

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CHAPTER 10

HEALTH AND REGULATORY CONSIDERATIONS

James Crook

INTRODUCTION

The State of California has long recognized the value of reusing wastewater and for many years has encouraged such reuse where public health is not compromised. Advances in wastewater treatment technology, including treatment reliability, allow the safe use of effluent for several purposes when reasonable precautions are taken.

The purpose of this chapter is (1) to summarize the health aspects of irrigation with reclaimed municipal wastewater, especially as related to pathogens, and (2) to describe the regulations in California that govern the reuse of treated wastewater.

HEALTH ASSESSMENT

Clearly, most wastewater reclamation and reuse operations impose a greater risk of public or worker exposure to pathogens or toxic substances than would the use of unpolluted waters of non-sewage origin. The objective, therefore, is to minimize the exposure and reduce the potential health hazards to acceptable levels. In general, the health concern is in proportion to the degree of human contact with the water, the quality of the effluent, and the reliability of the treatment processes.

The contaminants in reclaimed water that are of health significance may be grossly classified as biological and chemical agents. For most of the uses of reclaimed water, biological agents pose the greatest health risks, and quality standards are properly directed at these agents. Control of chemical contaminants is necessary for higher uses of reclaimed water, where the public is more directly exposed and ingestion of the reclaimed water or its constituents is more likely.

From a public health standpoint, the major chemical constituents of concern are the toxic heavy metals, pesticides, and other organic contaminants that may cause adverse long-term health effects. The mechanisms of food contamination include: physical contamination, where evaporation and repeated application may result in a build-up of contaminants on crops; uptake through the roots from the applied water or the soil; and foliar uptake. Groundwater contamination by chemical and biological constituents is discussed in Chapters 12 through 15.

While there is a paucity of information regarding the health significance of many of the known or suspected carcinogenic, mutagenic, or teratogenic organic constituents that may be present in wastewater used for crop irrigation, some chemical constituents are known to accumulate in particular crops and thus may present health hazards to both grazing animals and humans [1]. The chemical constituents of wastewater and the effect of treatment processes on them are discussed in Chapter 2. The effects of chemical constituents on plant growth and soils are discussed in Chapters 3 and 7, and the fate of metals and trace organics in the soil is covered in Chapters 13 and 15.

Types of Microorganisms

Properly operated state-of-the-art wastewater treatment plants can reduce pathogen concentrations by many orders of magnitude. However, it is difficult to assure complete, continuous elimination of pathogens, and the potential for disease transmission through water reuse has not been eliminated. In general, the disease organisms responsible for epidemics in the past are still present in today's sewage. Good sanitary engineering practice results in control rather than total eradication of the disease agent.

The numbers of pathogens in sewage have markedly declined over the decades as a result of disease control with antibiotics and improved sanitary conditions and practices. During an outbreak, pathogen numbers in local sewage go up, and it would be inappropriate to be careless simply because present pathogen densities may be relatively low. The principal infectious agents that may be present in raw sewage may be classified into three broad groups: bacteria, parasites (protozoa and helminths), and viruses. Table 10-1 summarizes the major infectious agents potentially present in raw domestic wastewater.

Table 10-1. Major pathogens potentially present in raw domestic wastewater.

Pathogen	Disease
Protozoa	
Entamoeba histolytica	Amebiasis (amebic dysentery)
Giardia lamblia	Giardiasis
Balantidium coli	Balantidiasis (dysentery)
Helminths	
Ascaris lumbricoides (Roundworm)	Ascariasis
Ancylostoma duodenale (Hookworm)	Ancylostomiasis
Necator americanus (Roundworm)	Necatoriasis
Ancylostoma (spp.) (Hookworm)	Cutaneous Larva Migrans
Strongyloides stercoralis (Threadworm)	Strongyloidiasis
Trichuris trichiura (Whipworm)	Trichuriasis
Taenia (spp.) (Tapeworm)	Taeniasis
Enterobius vermicularis (Pinworm)	Enterobiasis
Echinococcus granulosus (spp.) (Tapeworm)	Hydatidosis
Bacteria	
Shigella (4 spp.)	Shigellosis (dysentery)
Salmonella typhi	Typhoid fever
Salmonella (~1700 spp.)	Salmonellosis
Vibrio cholerae	Cholera
Escherichia coli (enteropathogenic)	Gastroenteritis
Yersinia enterocolitica	Yersiniosis
Leptospira (spp.)	Leptospirosis
Viruses	
Enteroviruses (71 types) (polio, echo, Coxsackie)	Gastroenteritis, heart Anomalies, meningitis, others
Hepatitis A virus	Infectious hepatitis
Adenovirus (31 types)	Respiratory disease
Rotavirus	Gastroenteritis
Parvovirus (2 types)	Gastroenteritis

Bacteria

One of the most common pathogens found in municipal wastewater is the bacteria of the genus *Salmonella*. This group contains a large number of species that can cause disease in humans and animals. There are three distinct forms of salmonellosis in humans: enteric fevers, septicemias, and acute gastroenteritis. The most severe enteric fever form of salmonellosis is the typhoid fever caused by *Salmonella typhi*. At one time, typhoid fever was so prevalent that death rates of more than 50 per 100,000 population were not uncommon in cities in the United States. Now, however, death due to this disease is practically nonexistent [2]. The most common form of *Salmonella* isolated from human sources in the United States is *Salmonella typhimurium*. Approximately 1500 serotypes are known, but only 200 or so different types are detected in any one year [3].

There are a variety of other bacteria of lesser importance that have been isolated from sewage. These include *Vibrio, Mycobacterium, Clostridium, Leptospira,* and *Yersinia* species. Although these pathogens may be present in wastewater, their concentrations are usually too low to initiate disease outbreaks.

Waterborne gastroenteritis of unknown cause is frequently reported, and the suspected agent is bacterial. One potential source of this disease is certain gram-negative bacteria normally considered nonpathogenic. These include enteropathogenic *Escherichia coli* and certain strains of *Pseudomonas*, which may affect the newborn [4]. Recently, *E. coli* has been implicated in outbreaks of travelers' diarrhea [5], probably through production of an endotoxin in the small intestine.

In recent years, *Campylobacter coli* has been identified as the cause of a form of bacterial diarrhea in humans. Although it has been well-established that this organism causes disease in animals, it has only recently been implicated as the etiologic agent in waterborne disease outbreaks. One of these outbreaks in the United States involved 2100 cases [1].

Parasites

There are a variety of protozoan and metazoan agents that are pathogenic to humans and that may be found in municipal wastewater. Probably the most serious of the parasites is the protozoan *Entamoeba histolytica*, which is responsible for amoebic dysentery and amoebic hepatitis. These diseases occur worldwide, although the incidence in the United States is not well-documented.

Another protozoan, the flagellate *Giardia lamblia,* is the cause of the disease giardiasis, which is responsible for gastrointestinal disturbances, flatulence, diarrhea, and discomfort and is emerging as a major waterborne disease. As is the case with *E. histolytica,* the cystic form of *G. lamblia* is the infective agent, and it also exhibits resistance to chlorine disinfection [6]. The number of outbreaks and cases of giardiasis has increased significantly in recent years [7], with one outbreak in 1974-75 affecting 4800 people in Rome, New York. At present, *Giardia* is the most common disease-causing intestinal parasite in the United States.

Several helminthic parasites may be found in wastewater. The most important are intestinal worms, including the stomach worm *Ascaris lumbricoides,* the tapeworm *Taenia saginata,* the whipworm *Trichuris trichiura,* the hookworms *Ancylostoma duodenale* and *Necator americanus*, and the threadworm *Strongyloides stercoralis.* Many of the helminths have complex life cycles, including a required stage in intermediate hosts. The infective stage of some helminths is either the adult organism or larva, whereas in other helminths the eggs or ova constitute the infective stage of the organisms. The eggs and larvae are resistant to environmental stresses and can be expected to survive usual wastewater disinfection procedures.

Viruses

Viruses are obligate intracellular parasites that are able to multiply only within a host cell. Enteric viruses are those that multiply in the intestinal tract and are released in the feces of infected persons. Over 100 different enteric viruses capable of producing infections or disease are excreted by humans.

The most important human enteric viruses are the enteroviruses (polio, echo, and Coxsackie), rotaviruses, reoviruses, parvoviruses, adenoviruses, and hepatitis A virus [6,8]. Hepatitis A, the virus causing infectious hepatitis, is the virus most frequently reported and documented to be transmitted by contaminated water. No host other than man has been found for the hepatitis virus. In spite of the inability to successfully cultivate the etiologic agent in the laboratory, there is irrefutable epidemiological evidence available to incriminate water as the vehicle of transmission of hepatitis A [9,10,11,12]. Several investigators have found viruses in groundwater, and groundwater has been implicated in several disease outbreaks of viral origin [13]. There have been many other viral disease outbreaks where water has been suspected as transmitting the viral agent; however, in most cases, the evidence has not been conclusive [14,15].

Although many incidents of waterborne transmission of viruses undoubtedly are not recognized, investigated, or reported, the available epidemiological data indicate that the role of water in the overall incidence of viral diseases may be limited [16,17,18] and that other modes of transmission, such as personal contact, probably are responsible for the great majority of viral diseases [19]. Even though water may not play an important role in the overall transmission of viral diseases, the potential public health significance of viruses in water should not be neglected or underestimated. Theoretically, any excreted virus capable of producing infection when ingested could be transmissible by inadequately treated wastewater [20].

Mechanisms of Disease Transmission

Disease can be transmitted to humans either directly by contact, ingestion, or inhalation of infectious agents in reclaimed water, or indirectly by contact with objects previously contaminated by the reclaimed water. The following circumstances must occur for a person to become ill: (1) the infectious agent must be present in the community producing the wastewater and, hence, in the wastewater from that community; (2) the agents must survive all the wastewater treatment processes to which they are exposed; (3) the person must either directly or indirectly come in contact with the effluent; and (4) the agents must be present in sufficient numbers at the time of contact to cause illness.

Contact with infectious agents does not always result in illness. Whether illness occurs depends on a series of complex interrelationships between the host and the infectious agent. Specific variables include the numbers of the invading microorganism (dose), the numbers of organisms necessary to initiate infection (infective dose), the organism's ability to cause disease (pathogenicity), the degree to which the microorganism can cause disease (virulence), and the relative susceptibility of the host.

Susceptibility is highly variable and dependent upon both the general health of the subject and the specific pathogen in question. Infants, elderly persons, malnourished persons, and persons with concomitant illness are more susceptible than healthy adults.

As an example of the variability in infective doses, studies have shown that 10 or less *Giardia lamblia* and as few as 10 *Shigella dysentariae 1* can cause illness, whereas it may require as many as 1,000 *Vibrio cholerae* or 10,000 *Salmonella typhi* to initiate disease [21]. In one volunteer study, about 25 percent of the subjects who ingested 180 *Shigella Flexneri 2A* were infected and made ill [22]. It has been reported that a maximum of 20 *Entamoeba histolytica* cysts constitutes an infective does [23], and very low numbers of viruses may be able to initiate disease in humans. Toxigenic organisms such as enteropathogenic *Escherichia coli* and *Clostridium perfringens* may require 1×10^{10} organisms per dose [9].

For most organisms, infections occur at lower doses than are required to cause disease. Infection is defined as an immunological response to pathogens by a host without showing clinical signs of disease.

It is impossible to accurately predict the type or concentration of microorganisms in raw wastewater. Table 10-2 illustrates the range of concentration of certain organisms that may be present in municipal wastewater. The general health of the contributing population, the existence of disease carriers in the population, and the ability of infectious agents to survive outside their hosts under a variety of

Table 10-2. Microorganism populations in untreated domestic wastewater [23,29].

Organism	Concentration (No./mL)
Coliform	$0.5\text{-}1 \times 10^6$
Fecal streptococci	$5\text{-}20 \times 10^3$
Shigella	Present
Salmonella	4-12
Pseudomonas aeroginosa	102
Clostridium perfringens	507
Mycobacterium tuberculosis	Present
Protozoan cysts	100
Helminth ova	1
Enteric virus	1-492

environmental conditions all contribute to the occurrence and concentration of pathogens in a particular wastewater.

Since enteroviruses are not normally excreted for prolonged periods by healthy individuals, their occurrence in municipal wastewater fluctuates widely. Viruses shed from an infected individual commonly range from 1,000 to 100,000 infective units per gram of feces [2]. Not every virus that is present in feces is waterborne, however, and many may persist for only a short time in municipal wastewater. It has been calculated that the average enteric virus density in municipal sewage is about 500 units/100 mL [24]; this number may vary considerably. In water-short areas such as Israel, where water use is conservative, concentrations in sewage have been reported to average from 600 to 49,200 plaque-forming units (PFU)/100 mL [25]. Virus densities in sewage are also quite seasonal and are most frequently isolated during the summer and early autumn.

Removal of Microorganisms by Wastewater Treatment Processes

Primary treatment, which is merely a sedimentation process, has only limited effect on the removal of most biological species present in the wastewater. Some of the larger and heavier organisms, such as the eggs of helminths and cysts of protozoa, will settle out during primary treatment, and particulate-associated microorganisms may be removed with settleable matter. Between 50% and 90% of the parasitic eggs and cysts can be removed by primary settling, whereas as little as 25% of the bacteria may be removed during the sedimentation process [26]. Primary treatment does not effectively reduce the level of bacteria or viruses in sewage [27,28].

Conventional biological treatment processes (trickling filters, activated sludge, and oxidation ponds) reduce the quantities of biological organisms found in raw or settled sewage but do not eliminate them. The mechanism of removal is either adsorption or predation. In general, activated sludge processes are more effective in reducing bacteria and virus populations than are trickling filters. Activated sludge typically removes over 90% of the bacteria [29] and 80-90% of the viruses, while trickling filters typically remove 50-90% of the bacteria and the viruses [30,31]. Trickling filters have been shown to remove 30% of the beef tapeworm eggs and over 99% of *Entamoeba histolytic* cysts, whereas activated sludge processes by themselves appear to be ineffective in removing either cysts or eggs [32]. All types of secondary treatment can remove more than 90% of coliform indicator organisms, and, in theory, pathogen removals are in proportion to the reduction of coliforms.

The purpose of most advanced treatment processes is to remove either inorganic or organic constituents. Therefore, the removal of biological contaminants by these processes is only incidental in many cases and, generally, is not too great. An exception is reverse osmosis, which, depending on type of unit and membrane characteristics, degree of wastewater pretreatment, and other factors, can be very effective in removing most viruses and virtually all larger microorganisms. Activated carbon adsorption has been shown to adsorb some viruses from wastewater, but the adsorbed viruses can be displaced by organic compounds and enter the effluent [33,34].

Tertiary treatment consisting of chemical coagulation, sedimentation, and filtration has been shown to remove 99.5% of seeded virus [35]. In addition to effectively removing viruses, this treatment chain reduces the turbidity of the wastewater to very low levels, thereby enhancing the efficiency of the disinfection process that follows filtration. Filtration is also effective in removing the many larger parasites that are resistant to the disinfection levels normally used in wastewater treatment.

The most important treatment process from the standpoint of pathogen destruction is disinfection. In the United States, the most common disinfectant for both water and wastewater is chlorine. The efficiency of disinfection with chlorine is dependent upon the water temperature, pH, time of contact, degree of mixing, presence of interfering substances, concentration and form of the chlorinated species, and nature and concentration of the organisms to be destroyed.

In practice, the amount of chlorine added is determined empirically, based on desired residual and effluent quality, which is usually measured by total or fecal coliform concentration. Unless the wastewater has a very low turbidity, there is a high probability that the disinfected wastewater will not be completely free of bacterial or viral pathogens. In general, bacteria are less resistant to chlorine than are viruses, which in turn are less resistant than parasites.

The destruction of viruses by chlorine is highly variable. Studies [36] indicate that viruses are generally more resistant to chlorine than bacteria. Therefore, the coliform test does not give a reliable indication of the effectiveness of virus destruction by disinfection [37,38].

Ozone is not commonly used for disinfection but has received considerable attention in recent years. However, it is difficult to disinfect secondary effluents with ozone and consistently meet typical bacteriological standards for reclaimed water, because suspended matter reacts with the ozone and thereby leaves less of the ozone available for disinfection [39,40].

It is also possible to reduce the concentrations of bacteria and viruses in wastewater by storing it before use. One study of a test holding pond in Israel found that the concentrations of total coliforms, fecal coliforms, and fecal streptococci in secondary effluent were reduced 2-4 logs during both a 73-day storage time in winter and a 35-day storage time in summer. Enteroviruses were reduced from 1100/100 ml during the winter storage and from 200/100 ml during the summer storage to less than detectable levels during both storage seasons [41].

Survival of Pathogens

Under favorable conditions, enteric pathogens can survive for extremely long periods of time on crops or in water or soil. Factors that affect survival include number and type of organism, soil organic matter content, temperature, humidity, pH, amount of rainfall, amount of sunlight, protection provided by foliage, and competitive microbial flora. For example, a review of the literature [21,42,43] indicates that *Ascaris* ova can survive from 27 to 35 days on vegetables and 730-2010 days in soil, and *Salmonella* spp. can survive from 3 to more than 40 days on vegetables, more than 100 days on grass, and from 15 to more than 280 days in the soil. *Salmonella typhi* have been reported to survive 87-100 days in water, 2-120 days in soil, and

10-53 days on vegetables [42]. In one study, poliovirus and Coxsackie virus inoculated onto vegetables survived for more than four months during commercial and household storage [44] and up to 180 days in saturated soil at 4°C [45]. The range of survival times suggests that pathogens introduced into a field by irrigation with wastewater could survive in the soil or on some crops for extensive lengths of time. A more complete discussion of pathogen survival in soil and transport in percolating water is presented in Chapter 14.

Aerosols

The concentration of pathogens in aerosols is a function of their concentration in the applied wastewater and the aerosolization efficiency of the spray process [46]. Studies have shown that, during the spray irrigation of wastewater, the amount of water that is aerosolized can vary from less than 0.1% to almost 2% with the mean aerosolization efficiency varying from 0.32% to 1.3% [47,48,49,50]. Aerosols are defined as particles ranging from 0.01 to 50 μm in diameter that are suspended in air. Viruses and most pathogenic bacteria are in the respirable size range [51]; hence, a possible direct means of human infection by aerosols is by inhalation. Infection or disease can be contracted indirectly by deposited aerosols on surfaces such as food, vegetation, and clothes. The infective dose of many pathogens is lower for respiratory tract infections than for infections via the gastrointestinal tract; thus, inhalation may be a more likely route for disease transmission than either contact or ingestion [52].

In general, bacteria and viruses in aerosols remain viable and travel farther with increased wind velocity, increased relative humidity, lower temperature, and darkness [47,53,54]. Other important factors include the initial concentration of pathogens in the wastewater and droplet sizes. Studies have shown that relatively high concentrations of bacterial aerosols can be transmitted for considerable distances under optimum conditions. For example, one study found that coliforms were carried 295 to 426 ft (90-130 m) with a wind velocity of 3.4 mph (1.5 m/sec). The authors estimated that fine mist could be carried 984 to 1312 ft (300-400 m) with an 11 mph

(5 m/sec) wind and 3281 ft (1,000 m) or more with stronger winds [43]. Another study found that the mean net bacterial aerosol levels, i.e., the observed minus the simultaneous mean upwind value, were 485 colony-forming units (CFU)/m^3 at a distance of 69-98 ft (21-30 m) from the most downwind row of sprinkler heads in a spray field and 37 CFU/m^3 at 656 ft (200 m) downwind [50]. The sprayed wastewater had received treatment in stabilization lagoons before disinfection with chlorine.

During a recent study in Israel, echovirus 7 was detected in air samples collected 40 m downwind from sprinklers spraying secondary effluent [55]. Aerosol measurements at Pleasanton, California, where undisinfected secondary effluent was sprayed, indicated that the geometric mean aerosol concentration of enteroviruses obtained 50 m downwind of the wetted spray area was 0.014 PFU/m^3 [49]. This concentration is equal to one virus particle in 71 m^3 of air.

Studies [49,56,57] indicate that the use of the traditional indicator organisms to predict human exposure via aerosols results in a significant underestimation of pathogen levels. In those studies, the pathogens survived the wastewater aerosolization process much better than the indicator organisms.

Because there is a paucity of information concerning the health risks associated with wastewater aerosols, health implications regarding this subject are difficult to assess. Most of the epidemiological studies conducted on residents in communities subjected to aerosols from sewage treatment plants--many using subjective health questionnaires--have not detected any correlation between exposure to aerosols and illness. Although some studies have indicated higher incidences of respiratory and gastrointestinal illnesses in areas receiving aerosols from sewage treatment plants than in control areas, the elevated illness rates were either suspected to be the result of other factors, such as economic disparities, or were not verified by antibody tests for human viruses and isolations of pathogenic bacteria, parasites, or viruses [58,59].

The research conducted to date seems to indicate that the health risk associated with aerosols from sewage effluent spray irrigation sites is low, particularly for irrigation with wastewater that has been disinfected. However, sporadic cases may exist where high exposure is experienced, and until more sensitive and definitive studies are conducted to fully evaluate the ability of aerosols to cause disease, prudence dictates that the inhalation of aerosols that may contain viable pathogens should be minimized.

Disease Incidence Related to Wastewater Reuse

There is epidemiological evidence indicating that the reuse of municipal wastewater, particularly for the irrigation of food crops, has resulted in the transmission of disease [43,60]. The majority of documented disease outbreaks have been the result of bacterial or parasitic contamination. In all cases, either raw sewage or undisinfected effluent was the source of irrigation water. These outbreaks demonstrate that sewage is a hazardous material with a significant potential for transmission of infectious disease. However, there have not been any confirmed disease outbreaks in California resulting from the use of reclaimed wastewater.

Although there is little information concerning the occurrence of viral diseases resulting from the reuse of wastewater, the water route of transmission, such as public water supplies, has been implicated in several outbreaks of infectious hepatitis and poliomyelitis. The study of low-level or endemic occurrence of waterborne virus diseases has been virtually ignored for several reasons: (1) present virus detection methods are not sensitive enough to accurately detect low concentrations of viruses in large volumes of water; (2) enteric virus infections are often not apparent, thus making it difficult to establish the endemicity of such infections; (3) the apparently mild nature of most enteric virus infections preclude reporting by the patient or the physician; (4) damage due to enteroviral infections may not become obvious for several months or years [61]; and (5) once introduced into a population, person-to-person contact would become a major mode of transmission of an enteric virus, thereby obscuring the role of water in its transmission.

REGULATORY AUTHORITY IN CALIFORNIA

Wastewater reclamation in California is notable for the large number of reuse operations, the diversity of applications, and the excellent safety record over many years. The principal agencies involved in wastewater reclamation and reuse in California are the following: United States Environmental Protection Agency; Bureau of Reclamation, United States Department of the Interior; California Department of Water Resources; California State Water Resources Control Board; California Department of Health Services; local health agencies; and the nine California Regional Water Quality Control Boards. From a regulatory standpoint, the two federal agencies and the California Department of Water Resources play relatively minor roles in the area of wastewater reclamation.

The U.S. Environmental Protection Agency (EPA) provides the federal share of grants for funding municipal wastewater treatment projects and sets regulations to guide funding of wastewater reclamation projects and to ensure protection of the environment. The EPA also provides technical guidance on health and other issues related to wastewater treatment. The Bureau of Reclamation studies uses of reclaimed water and controls and administers loans under the Small Reclamation Projects Act of 1956. In addition, the Farmers Home Administration has grant and loan programs for small communities. Under appropriate conditions, these federal grants and loans can be used to finance distribution systems to transport reclaimed water from treatment plants to points of use. The California Department of Water Resources (DWR) studies the availability and reuse potential of wastewater, including the environmental effects of reuse. The DWR may also assist in funding research related to wastewater reuse and assists in identifying and planning new projects.

The State Water Resources Control Board (SWRCB) and the Regional Water Quality Control Boards (RWQCB) have the primary responsibility for controlling and protecting the quality of waters in California and for administering water rights. The SWRCB administers the Federal and State Clean Water Grant Program, which is the primary source of financial assistance to local public agencies for the construction of wastewater treatment and disposal facilities. Eligible facilities include treatment plants, conveyance facilities, and, under certain conditions, on-site distribution facilities. In 1977, the Office of Water Recycling was established within the SWRCB to promote wastewater reuse in California and coordinate statewide water reclamation activities.

The California Department of Health Services (DOHS) reviews individual reclamation requirements, project plans, and environmental documents and maintains a wastewater reclamation surveillance program to ensure an adequate degree of health protection. In addition, DOHS has the authority and responsibility under California law to establish health-related standards for wastewater reclamation for many uses, including irrigation. A part of the California Water Code known as the Porter-Cologne Water Quality Control Act [62] contains the enabling legislation for establishment of criteria, as follows:

> "13521. The State Department of Health Services shall establish statewide reclamation criteria for each varying type of reclaimed water where such use involves the protection of public health."

In addition, if it is determined that contamination exists as a result of use of reclaimed water, DOHS and/or local health agencies have the separate authority to order abatement of contamination and issue peremptory orders, as stated in the California Health and Safety Code, Part 3, Division 5, Chapter 6. DOHS also has cross-connection control regulations [63] governing the delivery system requirements with the specific purpose of maintaining strict separation between the reclaimed and domestic water systems. Local health agencies have independent authority and may, if they deem necessary, impose requirements more stringent than those specified by the California Department of Health Services.

The Water Code provides for the nine RWQCBs to establish water-quality standards, to prescribe and enforce waste discharge requirements in order to protect surface and groundwater quality, and, in consultation with DOHS, to prescribe and enforce reclamation requirements. Thus, DOHS's reclamation criteria are enforced by the regional boards, and each wastewater reclamation project must have a permit from the appropriate RWQCB conforming to the DOHS criteria. The relevant sections of the Water Code are as follows:

"13522.5. (a) Any person reclaiming or proposing to reclaim water for any purpose for which reclamation criteria have been established shall file with the regional board of that region a report containing such information as may be required by the board.

13523. Each regional board, after consulting with and receiving the recommendations of the State Department of Health and after any necessary hearing, shall, if it determines such action to be necessary to protect the public health, safety, or welfare, prescribe water reclamation requirements for water which is used or proposed to be used as reclaimed water. Requirements may be placed upon the person reclaiming water, the user, or both. Such requirements shall include, or be in conformance with, the statewide reclamation criteria established pursuant to this article. The regional board may require the submission of a preconstruction report for the purpose of determining compliance with the reclamation criteria.

3524. No person shall reclaim water or use reclaimed water for any purpose for which reclamation criteria have been established until water reclamation requirements have been established pursuant to this article or a regional board determines that no requirements are necessary."

In 1978 additions were made to the Water Code that, if specific conditions are met, require the use of reclaimed, rather than potable, water to irrigate greenbelt areas. The appropriate sections are as follows:

"13550. The Legislature hereby finds and declares that the use of potable domestic water for the irrigation of greenbelt areas, including, but not limited to, cemeteries, golf courses, parks, and highway landscaped areas, is a waste or an unreasonable use of such water within the meaning of Section two of Article X of the California Constitution when reclaimed water which the state board, after notice and a hearing, finds meets the following conditions is available:

(a) The source of reclaimed water is of adequate quality for such use and is available for such use.

(b) Such reclaimed water may be furnished to such greenbelt areas at a reasonable cost for facilities for such delivery. In determining reasonable cost, the state board shall consider all relevant factors, including, but not limited to, the present and projected costs of supplying potable domestic water to affected greenbelt areas and the present and projected costs of supplying reclaimed water to such areas, and shall find that the cost of supplying such reclaimed water is comparable to, or less than, the cost of supplying such potable domestic water.

(c) After concurrence with the State Department of Health Services, the use of reclaimed water from the proposed source will not be detrimental to public health.

(d) Such use of reclaimed water will not adversely affect downstream water rights, will not degrade water quality, and is determined not to be injurious to plant life.

The state board may require a public agency or person subject to this article to furnish such information as may be relevant to making the findings required by this section.

13551. A person or public agency, including a state agency, city, county, city and county, district, or any other political subdivision of the state, shall not use water from any source of quality suitable for potable domestic use for the irrigation of greenbelt areas when suitable reclaimed water is available as provided in Section 13550; provided that any such use of reclaimed water in lieu of the extraction of groundwater shall, to the extent of such reclaimed water so used, be deemed to constitute a reasonable beneficial use of the groundwater and such use of reclaimed water shall not cause any loss or diminution of any existing water right however acquired."

REGULATIONS

California Regulations

There is some risk of human exposure to pathogens in almost every wastewater reclamation operation, but in general the health concern is in proportion to the degree of human contact with the water and the adequacy and reliability of the wastewater treatment processes.

Pursuant to Section 13521 of the Water Code, the DOHS has established statewide reclamation criteria, which were revised most recently in 1978. A basic objective of DOHS's regulations, entitled "Wastewater Reclamation Criteria" [64], is to assure health protection without unnecessarily discouraging wastewater reclamation. The regulations specify wastewater reuse standards for uses involving irrigation, impoundments, and groundwater recharge. The regulations include water-quality standards, treatment process requirements, sampling and analysis requirements, operational requirements, and treatment reliability requirements. The required degree of treatment increases as the likelihood of human exposure to the wastewater increases. The treatment and quality requirements for the irrigation uses covered by the Wastewater Reclamation Criteria are summarized in Table 10-3. The reclamation criteria are intended to assure an adequate degree of health protection from disease transmission and do not specifically address the potential effects of reclaimed water on the crops or soil. The complete set of regulations is contained in Appendix D.

For most uses of reclaimed water, the regulations do not require an extensive monitoring program to demonstrate reclaimed water quality. Such a requirement would eliminate the many small reclamation operations that would not be able to afford the expense of a sizable monitoring effort. Consequently, insofar as possible without jeopardizing the regulatory intent, descriptive terms well understood by professionals in the wastewater treatment field are used rather than quantitative limits of specific parameters. For example, an "adequately oxidized wastewater" is required rather than effluent meeting a specific biochemical oxygen demand (BOD), suspended solids, or other parameter. However, analyses for these specific water quality parameters may be required by the RWQCBs as part of the effluent discharge requirements.

Table 10-3. Wastewater treatment and quality criteria for irrigation [64].

Treatment level	Coliform limits	Type of use
Primary		Surface irrigation of orchards and vineyards
		fodder, fiber, and seed crops
Oxidation and disinfection	$\leq$23/100 mL	Pasture for milking animals
		Landscape impoundments
		Landscape irrigation (golf courses, cemeteries, etc.)
	$\leq$2.2/100 mL	Surface irrigation of food crops (no contact between water and edible portion of crop)
Oxidation, coagulation, clarification, filtration[a], and disinfection	$\leq$2.2/100 mL max. = 23/100 mL	Spray irrigation of food crops
		Landscape irrigation (parks, playgrounds, etc.)

a. The turbidity of filtered effluent cannot exceed an average of 2 turbidity units during any 24-hour period.

Crop Irrigation

Wastewater containing pathogens can contaminate crops directly by contact during irrigation or indirectly as a result of soil contact. Crops can also be contaminated by blowing dust or by workers, birds, and insects that convey organisms from irrigation water or soil to the edible portion of the crop.

Where there is a minimal health risk, based on degree of contact and water quality, the regulations are extremely liberal and require a very low level of treatment. Primary effluent is acceptable for the surface or spray irrigation of fodder, fiber, and seed crops and for the surface irrigation of orchards and vineyards. Primary effluent is defined [64] as "effluent from a wastewater treatement plant process which provides removal of sewage solids so that it contains not more than 0.5 mL/L of settleable solids as determined by an approved laboratory method." Primary sedimentation usually removes less than 50% of coliforms and pathogenic bacteria from sewage, and it is relatively ineffective in removing viruses and protozoa [21,27,28].

Primary effluent has been used for the surface irrigation of orchards and fodder, fiber, and seed crops for more than 60 years without any observed detrimental health effects [65]. With proper application and use area controls, human contact with the wastewater is minimal. Allowing the fields to dry before grazing or harvest of fodder crops substantially reduces the number of viable pathogens on the crop before animal consumption. Although there has not been any apparent increase in beef tapeworm infections in California resulting from the use of primary effluent for pasture irrigation, no detailed studies have been conducted to determine whether such infections are more prevalent in cattle grazing on pasture irrigated with primary effluent than in cattle grazing on pasture irrigated with water of non-sewage origin.

Primary effluent is also acceptable for the surface irrigation of orchards and vineyards because of the distance between the irrigated ground and the edible crops. Pathogens in the wastewater do not readily penetrate into fruits or vegetables unless the skin is broken [21]. In one study where soil was inoculated with poliovirus, viruses were detected in the leaves of plants grown in the soil only when the plant roots were damaged or cut [66]. Although absorption of virus by plant roots and subsequent acropetal translocation has been reported by Murphy and Syverton [67], the authors noted that it probably does not occur with sufficient regularity to be important as a mechanism for transmission or for interepidermic survival of virus. Therefore, the likelihood of translocation of pathogens through the trees or vines to the edible portions of the crops is extremely low, and the health risks are negligible. The regulations prohibit harvesting of fruit that has come in contact with the irrigation water or the ground.

As previously stated, many pathogens can survive for extended periods on plants and in soil; thus, simply providing extensive periods between irrigation and crop harvest, or providing commercial storage before public sale, cannot be relied upon to eliminate all pathogens. Consequently, in the case of food crops, emphasis should be placed on eliminating the pathogens from the wastewater before irrigation, processing the crop to destroy pathogens before public sale, or preventing direct contact between the wastewater and the edible portion of the crop to minimize the risks of disease transmission.

The risks vary depending on the type of crop and method of irrigation. If food crops are surface-irrigated such that there is no contact between the edible portion of the crop and the reclaimed water, a disinfected, secondary-treated effluent is acceptable. The wastewater is considered adequately disinfected if at some location in the treatment process the median number of coliforms does not exceed 2.2/100 mL. The median value is determined from the bacteriological results of the last seven days for which analyses have been completed, and, as in all sections of the regulations specifying coliform limits, daily sampling is required.

As indicated above, the regulations require sampling the effluent for coliforms rather than testing for infectious agents directly. In recognition of the many constraints associated with analyzing wastewater for all of the potential pathogens that may be present, it has been common practice to use a microbial indicator or surrogate to indicate fecal contamination of water. Testing for all pathogens would require use of a vast number of tests, some of which involve complex, time-consuming, expensive, and often insensitive procedures. Further, the concentrations of different pathogens vary in different wastewaters, which may make detection difficult and unreliable. This variability is a function of the number of intestinal infections that occur at different times in the contributing warm-blooded population and is independent of the concentrations of nonpathogenic indicator organisms.

The total coliform group contains bacteria that are always in the intestinal tract of humans and other mammals. Coliforms occur naturally in the feces of warm-blooded animals in higher concentrations than pathogens and are easily and unambiguously detectable, exhibit a positive correlation with fecal contamination, and generally respond similarly to environmental conditions and treatment processes as many pathogens. Consequently, the DOHS has selected the total coliform group of bacteria as the indicator organism to determine the presence or absence of fecal contamination in water and at the same time suggest the presence or absence of infectious agents. Although it is true that the total coliform group includes strains that are not directly associated with fecal matter, the total coliform indicator system is not overly conservative. There have been instances where the total coliform test has not indicated the presence of waterborne *Salmonella* and *Giardia*, and the coliform group is known to be less resistant to chlorine disinfection than some pathogenics, such as protozoan cysts and enteric viruses.

The total coliform limits prescribed in the Wastewater Reclamation Criteria are based on the multiple tube fermentation technique and are reported in terms of the Most Probable Number (MPN). In the multiple tube procedure, replicate tubes of a selected test medium are inoculated with serial dilutions of a water sample. The greater the number of replicates of each sample volume in a dilution series, the greater the test precision. The MPN is actually an estimate based on certain probability formulas. For example, for an MPN index of less than 2.2/100 mL, the 95% confidence limits are between 0 and 6/100 mL, when five 10-mL portions are used in the analysis [68].

Because of the short distances between the irrigating water and the crops in most surface-irrigation systems, there is a likelihood of occasional contact between the wastewater or contaminated soil and crop as a result of splashing, transmission by vectors, windblown dust, or flooding caused by overapplication of the reclaimed water. However, in consideration of the relatively low frequency of such occurrences, it would be unrealistic to require that the irrigation water be free of all infectious agents. Typically, wastewater meeting a total coliform limit of 2.2/100 mL must receive a high level of treatment and, while the effluent not assuredly pathogen-free, it does not impose undue health risks when used for the surface irrigation of food crops.

Spray irrigation of food crops requires much more stringent requirements than surface irrigation because of the direct contact between the wastewater and the crops. Organisms contaminating food crops remain viable on the food surface unless they succumb to desiccation, exposure to sunlight, starvation, or action of other organisms or chemical agents. The reliability and completeness of pathogen inactivation by these mechanisms are questionable. Therefore, tertiary effluent that is pathogen-free is required for the spray irrigation of all crops that are eaten or sold raw. The surface irrigation of root crops, such as carrots, beets, and onions, also results in direct contact between the crop and the wastewater; hence, irrigation of those crops is subject to the same requirements.

The DOHS recognizes that identification and enumeration of viruses in water and wastewater is hampered by the limitations of sampling techniques, problems of concentration of samples, the complexity and high cost of laboratory procedures, and the limited number of facilities having the personnel and equipment necessary to perform the analysis. Furthermore, the laboratory culturing procedure to determine the presence or absence of viruses in a water sample takes about 14 days. Therefore, in lieu of a virus standard, the treatment and quality requirements stated above are specified, in part, to assure that the wastewater will not contain any pathogens, including viruses.

Selection of the treatment chain specified in the Wastewater Reclamation Criteria was predicated on studies conducted several years ago to determine the virus removal capability of advanced waste-treatment processes. More recent studies [35,69] have verified the effectiveness of the treatment chain, which includes oxidation, chemical coagulation, clarification, filtration, and disinfection. Data indicate that wastewater receiving such treatment and meeting specific constituent levels will be essentially free of all measurable pathogens. The quality requirements include the total coliform limit of 2.2/100 mL and turbidity limits. The turbidity standard is tied to the definition of filtered wastewater, which states that the turbidity cannot exceed an average of 2 turbidity units and cannot exceed 5 turbidity units more than 5% of the time during any 24-hour period. The regulations require that turbidity analyses shall be performed by a continuous recording turbidimeter. Experience has shown that these turbidity levels are readily achieved in well-operated wastewater treatment facilities employing chemical coagulation and filtration-unit processes and greatly enhance the effectiveness of the subsequent disinfection process.

Exceptions may be made to the quality requirements for reclaimed water used for the irrigation of food crops that undergo sufficient physical or chemical commercial processing to destroy pathogens before they are sold for human consumption. Exceptions are subject to approval by the DOHS based on a thorough evaluation in each case of the ability and reliability of the processing to destroy pathogens. Because of opportunities for transmission of infectious organisms created by handling crops that may be contaminated, it is not acceptable to sell the crops or otherwise allow the public to handle them before processing. This provision assures that the transmission link is severed and that contaminated raw foods are not brought into food-preparation environments.

There are no specific regulations in California pertaining to the packaging, distribution, or sale of food crops grown with reclaimed municipal wastewater. The DOHS has taken the position that properly designed and operated food crop irrigation projects meeting all appropriate standards do not present undue health risks to the consumer, and the DOHS will not require or recommend special labeling informing the public that the crops were irrigated with reclaimed wastewater.

Landscape Irrigation

The Wastewater Reclamation Criteria differentiate between types of landscape irrigation based on public access to the use area and expected exposure to the wastewater. Section 60313 of the regulations (Appendix D) covers landscape irrigation.

Wastewater that has received secondary treatment and has been disinfected to a level of 23 total coliforms per 100 mL (as required for landscaping) may contain both bacterial and viral pathogens, so direct contact with the water should be avoided. However, assuming that irrigation occurs when the public is excluded from the use area and that there is sufficient time for the grounds to dry out before use, there will not be any direct contact with the wastewater, and the health risks are dependent on indirect contact only--contact with grass, shrubs, objects, etc. that were previously wet with the reclaimed water. Indirect contact of this nature is relatively infrequent at the types of use areas identified in part (a) of Section 60313 (golf courses, freeway landscapes, and cemeteries) and does not warrant requiring the wastewater to be free of all infectious agents.

On the other hand, parks, playgrounds, schoolyards, and similar areas are more intensely used areas, and children may be more susceptible to some of the pathogens typically found in sewage. Therefore, the quality and treatment requirements for this type of landscape irrigation are identical to those required for the spray irrigation of food crops.

The possibility of disease transmission by aerosols or windblown spray from landscape irrigation sites must also be considered, because of the proliferation of reuse projects in urban settings or adjacent to populated areas. The degree of hazard depends on several factors, including degree of wastewater treatment, extent of aerosol or water-droplet travel, proximity to populated areas or areas accessible to the public, prevailing climatic conditions, and design of the irrigation system.

Although the regulations state that secondary treated wastewater meeting a total coliform requirement of 23/100 mL is acceptable for golf course irrigation, the DOHS has taken the position that a higher quality effluent, i.e., that meeting the requirements specified in Section 60313(b) of the Wastewater Reclamation Criteria, is necessary in situations where reclaimed water spray or aerosols are not confined to the use area and reach populated areas. Experience has shown that it is virtually impossible to prevent wastewater sprays or aerosols generated at golf courses from reaching private residential areas that abut fairways and/or greens. Therefore, the DOHS recommends that reclaimed water used to irrigate golf courses where residential property lots abut the fairways or greens be essentially pathogen-free and, hence, comply with Section 60313(b) of the Wastewater Reclamation Criteria.

While the Wastewater Reclamation Criteria require specific treatment unit processes in conjunction with effluent quality requirements, other unit processes may provide equivalent levels of treatment. The regulations are not intended to stifle research, development, and implementation of alternative or innovative treatment schemes, and the reclamation criteria include a section that addresses this issue. Section 60320.5 states that methods of treatment other than those mentioned in the Wastewater Reclamation Criteria may be acceptable if they can be demonstrated to be equivalent to the treatment methods specified in the regulations.

Treatment Reliability

The need for adequate treatment is obvious, but it is not so clearly recognized that there is an equally important need to assure reliability of treatment. Several field investigations of municipal wastewater treatment plants in California have documented that, until recently, wastewater treatment reliability has been a neglected phase of treatment plant design, construction, and operation [70,71,72,73]. The increase in reclamation operations and the more frequent use of reclaimed wastewater in public areas has increased the population that may be exposed to wastewater; consequently, the potential for illness resulting from an improperly treated water being delivered to the use areas has also increased. Thus, it is apparent that provisions are necessary to ensure reliability of treatment if a minimum health risk is to be maintained during the use of reclaimed municipal wastewater.

The Wastewater Reclamation Criteria contain both design and operational requirements necessary to ensure a minimum level of treatment reliability. Reliability features are described in Appendix D. Regardless of the automation built into a plant, mechanical equipment is subject to breakdown, and qualified, well-trained operators are an absolute necessity to assure reliable production of an acceptable water. This is reflected in the regulations, and certified personnel are required at all wastewater reclamation plants.

From a public health standpoint, provisions for adequate and reliable disinfection are the most essential features of the treatment process. Where disinfection is required, the reclamation criteria specify that a number of features must be incorporated into the system to ensure uninterrupted chlorine feed.

Most wastewater treatment facilities use fewer instruments and automatic control devices than closely related water-supply and chemical-processing plants. One nationwide study of 50 wastewater-treatment facilities found that the average secondary treatment plant allocates about 3% of construction costs for installed instruments, whereas water-supply and chemical-processing plants allocate about 6% and 8%, respectively [74]. If treatment-process efficiency and reliability are to improve, suitable measuring devices must be available to permit real time control. For example, automatic control loop systems that continuously monitor effluent chlorine residual and adjust the chlorine dosage to maintain a pre-determined residual are becoming increasingly prevalent at wastewater-reclamation facilities. Continuous recording turbidimeters, which automatically divert wastewater to intermediate storage ponds when the turbidity exceeds prescribed limits, have also proven to be effective control devices. Undoubtedly, as the need for adequate reliability becomes more widely recognized by regulatory and other control agencies, more sophisticated sensors, controllers, and recorders will be developed and utilized as integral components of wastewater-treatment systems.

In 1974, the EPA published a technical bulletin entitled "Design Criteria for Mechanical, Electric, and Fluid System and Component Reliability" [75] as a supplement to the 1970 Federal Guidelines for Design, Operation and Maintenance of Wastewater Treatment Facilities [76]. This bulletin spells out minimum design requirements and gives guidance on design for high reliability.

EPA's Municipal Environmental Research Laboratory recently published a handbook entitled "Identification and Correction of Typical Design Deficiencies at Municipal Wastewater Treatment Facilities" [77]. The handbook describes deficiencies that contribute to performance and reliability problems, poor safety practices, and/or decreased flexibility of plant process control. It is intended to provided guidance that will make designs more operable and maintainable at less cost, as well as more flexible in providing adequate performance during times of changing influent characteristics.

A national study of 103 biological wastewater treatment plants found that the ten major causes of poor plant performance were attributable to inadequate or incorrect sampling and testing procedures for process control, improper technical guidance, ineffective operation and maintenance manual instruction, and significant design deficiencies [78]. One of the study recommendations was that federal and state regulatory efforts be directed toward enforcement and accountability to encourage optimum performance from existing facilities. A similar study of 50 treatment plants found that only 13 of the 50 facilities consistently met minimum secondary treatment standards and that of the top ten, factors limiting performance were process-design-oriented [79].

An investigation of mechanical, electrical, and fluid system failures in 21 secondary treatment plants determined that 91% of the failures could have been prevented or mitigated if the reliability design criteria had been met [80]. Inclusion of reliability features, although lessening the probability that inadequately treated effluent will be discharged from the treatment plant, do not provide for failsafe reliability.

Other States and Countries

Several countries have developed standards governing the quality of wastewater used for irrigation purposes; in many cases, the standards are quite different from California's regulations. For example, in Germany, biological treatment and chlorination are required for the irrigation of pasture [81]. Irrigation of crops for human consumption that will be processed to kill pathogens must cease at least four weeks before harvesting. Potatoes and cereals are the only nonprocessed crops for which reclaimed water may be used for irrigation, and irrigation is allowed only through the flowering stage.

In South Africa, heavily chlorinated tertiary effluent is required for the irrigation of orchards, vineyards and fodder crops, and disinfected wastewater containing less than 1000 coliform organisms per 100 mL in 80% of the samples is used for processed food crops. The only nonprocessed food crops that can be irrigated with reclaimed water are fruits that are peeled before eating.

Wastewater reclamation activities in this country have generally been limited to water-short areas, particularly in the west and southwest. A few states other than California have independently developed, or are in the process of developing, reuse standards or guidelines, and as could be expected, they vary substantially. Brief summaries of existing or proposed guidelines and regulations from three states are given below to illustrate this variability.

The State of Texas does not have comprehensive wastewater reclamation regulations but does have guidelines for some irrigation uses. Undisinfected secondary effluent is allowed for pasture irrigation, and only food crops that will be processed are allowed to be irrigated with reclaimed water. Golf course irrigation requires a disinfected secondary effluent having a maximum BOD of 20 mg/L, a maximum suspended solids level of 20 mg/L, and a fecal coliform limit of 200/100 mL. Irrigation is not allowed at landscape areas that have uncontrolled access, such as parks and playgrounds.

Proposed regulations in Florida require that reclaimed water used to irrigate fodder crops, sod farms, or similar areas where public access is restricted must be secondary effluent. That effluent must be disinfected to produce a combined chlorine residual of 0.5 mg/L after 15 min of contact at maximum daily flow or after 30 min contact time at average daily flow, whichever provides for the higher level of public health protection. This basic disinfection level cannot result in more than 200 fecal coliform organisms per 100 mL of effluent sample. For the irrigation of golf courses, cemeteries, parks, and other landscaped areas accessible to the public, it is proposed to require advanced waste treatment and disinfection such that fecal coliforms in the effluent are below detectable limits and maximum BOD and total suspended solids are below 20 mg/L and 5 mg/L, respectively. Maintenance of 1 mg/L total chlorine residual for 15 min contact time at maximum daily flow or after 30 min contact time at average daily flow would also be required.

The State of Arizona has proposed regulations that do not require specific treatment processes but do prescribe effluent quality limits for various types of irrigation uses. From a practical standpoint, secondary treatment is the minimum necessary for any type of irrigation use, including fodder, fiber, or seed crop irrigation. Playground irrigation requires that the fecal coliform level in the effluent not exceed a geometric mean of 25 colony-forming units (CFU) per 100 mL with a maximum allowable level of 75 CFU per 100 mL in any sample, in addition to a turbidity limit of five turbidity units and an enteric virus limit of 125 PFU per 40 L. The proposed regulations for unprocessed food crop irrigation are even more stringent. They specify that the fecal coliform level in the effluent cannot exceed a geometric mean of 2.2 CFU/100 mL or 25 CFU/100 mL in any sample. Also, the maximum allowable turbidity is one turbidity unit, and it is specified that the final effluent cannot contain more than one virus PFU per 40 L.

Use Area Controls

The management of the reclaimed water once it leaves the treatment facility is an important facet of the overall reclamation operation. In order to minimize health risks and aesthetic or other problems, tight controls should be imposed on the delivery and use of the water. Failure to adhere to use restrictions can lead to health and public acceptance problems fully as serious as those associated with failure in the treatment system.

It was previously stated that in California, the regulations for any specific use are based on the expected degree of contact with the reclaimed water. The anticipated degree of contact, in turn, is based on compliance with proper design and operational controls at the use area. In recognition of the need to minimize health risks during delivery and at the point of reuse, the California Department of Health Services has developed use area guidelines that describe appropriate safety precautions and operational procedures, such as cross-connection control provisions, color-coded reclaimed water lines and appurtenances, key-operated valves and outlets, fencing, signs, control of aerosols and windblown spray, and provisions for worker protection.

Water reclamation requirements adopted by the RWQCBs normally include specific use restrictions appropriate for that individual project. Experience indicates that the key to assuring compliance with use area restrictions is careful project design, especially when extraordinary diligence would be required of the user in the absence of such design.

<u>Cross-Connection Control</u>

The reclaimed water transportation and distribution pipelines and appurtenances must be kept completely separate from the potable water systems. At service connections, the public water supply should be protected by an air-gap separation, a reduced-pressure-principle backflow-prevention device, or other protective devices acceptable to the regulatory agency. Although studies [82,71] have shown that cross-connections are not frequently found at use areas, cross-connection control regulations should be strictly enforced to assure that unnecessary risks are avoided.

Reclaimed water piping might easily be mistaken for that of domestic water if it is not properly identified. There are various ways to diminish the possibility of cross-connections at the use area. The reclaimed water lines and appurtenances can be color-coded or similarly marked for easy identification by workers. It may be possible to use different piping material for reclaimed and potable water lines. Complete records should be kept showing the plans and specifications of all types of water lines at the use area, and no water lines should be tapped into without first consulting these plans to ensure against cross-connections.

All valves and outlets from the reclaimed water system should be tagged with an appropriate warning, in addition to being color-coded, banded, or similarly marked for identification. Where hose bibbs are present on domestic and reclaimed water lines, it is advisable to establish differential sizes to preclude interchange of hoses.

Maximum attainable separation of reclaimed water lines and domestic water lines should be practiced in order to minimize construction accidents resulting in pipeline breaks, infiltration of wastewater from leaking reclaimed water lines into domestic water lines, or accidental cross-connection between reclaimed water and domestic water systems. The appropriate regulatory agency should be consulted regarding the type of piping materials that may be used for the reclaimed water lines.

Prevention of Public Contact

Adequate means of notification should be provided to inform the public that reclaimed water is being used. Such notification should include the posting of conspicuous warning signs. Warning signs should clearly state that the water is reclaimed from sewage and, unless the water is pathogen-free, warn the public to avoid contact with the water. Signs should not merely state "Keep Out" or "No Swimming" but should state "Water Reclaimed from Sewage--Avoid Contact," "Reclaimed Wastewater--Do Not Drink," or other similarly clear, simple, and concise wording. These signs should be located in areas where the public will most likely see them, and the printing should be of a significant size that the signs can be read at a distance. The public should be effectively excluded from contact with low-quality reclaimed water used for irrigation by posting warning signs, or where necessary, by erecting fences.

A study [57] of 19 golf courses in California that use reclaimed water for irrigation showed that only three of the courses had an adequate number of warning signs, and only one course printed a warning notice on the score cards. Of 72 use areas of all types surveyed in that study, less than one-fourth provided adequate public warning signs.

All valves, outlets, and/or sprinkler heads should also be appropriately tagged to warn the public that the water is not safe for drinking or bathing and should be of a type that can only be operated by authorized personnel. To prevent indiscriminate use of reclaimed water, most use areas employ key-operated valves and outlets or quick-coupling devices.

Precautions should be taken to ensure that reclaimed water will not be sprayed on people, walkways, dwellings, passing vehicles, picnic tables, fresh-water sources, reservoirs, or areas not under control of the user. Drinking-water fountains at spray-irrigation sites should also be protected from direct or windblown spray. At any use area frequented by the public, there should be an adequate number of drinking fountains to obviate the need for drinking from the reclaimed water system. At areas such as parks and golf courses, pressure-operated pop-up sprinkler heads are commonly used that have covers flush with the ground surfaces when not in use. This type of sprinkler is effective in preventing people from attempting to wash or drink from the sprinkler heads. All landscape irrigation should be scheduled so that there is ample opportunity for drying before use.

The possibility of disease transmission by aerosols or windblown spray from spray irrigation sites must also be considered where the source of the water is sewage effluent that is not completely disinfected to eliminate pathogens. Design features that would reduce the public health risks associated with spray irrigation are: (1) effective disinfection of the wastewater before spray irrigation to reduce the potential for disease transmission, even if some drift did reach areas frequented by the public; (2) windbreaks or buffer zones around the irrigation areas; (3) low-pressure spray nozzles with large orifices to produce large water droplets and reduce the formation of fine mist, which would be more susceptible to dispersal by the wind; (4) low-profile sprinklers; and (5) surface methods of irrigation. If the proposed spray application site is relatively flat, it may be feasible to use either border or ridge and furrow types of irrigation. The potential for aerosol or fine mist formation would thus be eliminated, as it would be if drip irrigation were utilized.

Some operational features to lessen public health hazards are: spray only during periods of low wind velocity; do not spray when wind is blowing towards sensitive areas subject to aerosol drift or windblown spray; and irrigate at off-hours when the public would not be at areas subject to windblown spray. This could be done during the late night or early morning hours, so that there would be adequate time for the land, soil, and vegetation, to dry before public use.

Confinement of Discharge

The discharge of reclaimed water should be confined to the area designated and approved for discharge. Irrigation should be controlled to minimize ponding, and runoff should be confined and properly disposed.

There should be no runoff from irrigated areas unless it is conducted to approved disposal areas. Surface drainage from fields irrigated with undisinfected effluent contains pathogenic bacteria and viruses, which may seriously contaminate the receiving waters. Although the reclaimed water is considered safe under the controlled conditions maintained in the use area, its safety would become questionable if used outside that area. For example, children may drink runoff collecting in stream beds or bathe in holes containing effluent from the use area.

Ponding and runoff can be minimized through proper operational procedures, such as reducing the application rates and proper placement of sprinkers so that the water is not sprayed on impervious surfaces such as sidewalks and roadways. Adequate containment and disposal of runoff is also important from a legal point of view and will prevent unnecessary and costly lawsuits.

Operational Procedures

Proper planning, operation, and maintenance of water-reclamation use areas is advantageous from economic, aesthetic, and health standpoints. In many cases, especially at privately owned use areas receiving water from public entities, the wastewater supplier may guarantee a specific quantity and quality of reclaimed water. However, a contract may specify that the user must accept all or a set amount of the reclaimed water from a reclamation plant. The user may not be able to reuse all the water and would therefore have to find alternative disposal methods. Therefore, the use area water requirements should be accurately determined before contracting for reclaimed water, and contract provisions should be thoroughly studied before implementation of a reuse scheme.

Wastewater reclamation plants are not fail-safe, and there may be times when reclaimed water will not be delivered to the use area because of problems originating at the reclamation plants. For areas where a constant supply of water is required, the user should be prepared for such occurrences by having an alternative supply of water.

All equipment pertaining to the transport and use of the reclaimed water should be inspected routinely. Preventive maintenance will reduce undue losses of water from leaking pipes and faulty equipment in addition to minimizing the related health hazards.

Use area surveillance and monitoring is a neglected aspect of many reclamation operations. Responsible agencies must take a lead role in assuring that wastewater reclamation projects are designed and operated to fully protect public health. It is entirely appropriate to impose regulatory controls on the conveyance facilities and use area operational practices. Indeed, it would be irresponsible to assume that water-quality requirements are sufficient by themselves to ensure adequate public health protection.

Worker Protection

Adequate measures should be taken for the protection of employees at the various types of use area facilities. It is very important for employees who may come in contact with the reclaimed water to be aware of the potential health hazards involved and not become complacent regarding safety procedures. Before employees are allowed to work in the vicinity of reclaimed water, they should be instructed about the potential for disease transmission from reclaimed wastewater and the precautions they should take. This implies that the personnel in responsible charge of the use areas should themselves be knowledgeable in the health aspects of water reclamation. Everyone involved in the management or operation of a reuse project should maintain a high level of cautiousness, because there is always a potential for equipment failure and human error.

First-aid kits should be available at the use areas, so that all cuts and abrasions can be treated promptly to prevent infection. Although skin contact with the reclaimed water can result in dermatitis and other skin rashes, open wounds are especially susceptible to infection by pathogens, as they present a ready mode of entry into the body. All employees who occasionally come in contact with reclaimed water should change from their work clothing and thoroughly wash before leaving the use area.

At crop-irrigation sites, precautions should be taken to avoid contamination of food taken to irrigated areas, and food should not be taken to areas still wet with reclaimed water. Provisions should also be made for a supply of safe drinking water for field workers. Such water should be carried in contamination-proof containers and protected from contact with reclaimed water or dust. Food and drinking-water containers should not be placed directly on the ground.

PUBLIC ATTITUDES

Historically, decisions to reuse wastewater for beneficial purposes--mostly uses involving minimal public contact--have been based on two principal factors, as discussed in Chapter 1: economics and the need for additional water. Many projects in recent years have involved uses where direct or indirect contact with reclaimed water is likely, and it is becoming clear that public involvement is to be reckoned with in the decision-making process. In recent years, the public sector has become increasingly aware of water pollution and environmental concerns, and public opinions should be carefully considered in any wastewater-reuse program.

Most public-attitude surveys have been directed at reaction toward direct domestic reuse of reclaimed water. Results of five major studies [83,84,85,86] using probability sampling procedures to assess public attitudes toward the use of reclaimed water for drinking are remarkably consistent: somewhat over 50% of each sample selected was opposed to the use of reclaimed water for the highest contact uses. On the other hand, a sizable portion of each sample, on the order of 40%, did not oppose, was positive toward, or would positively accept use of reclaimed water for drinking. A study [87] of 221 respondents of five U.S. cities using a non-probability sampling procedure registered the highest rate of public acceptance, where 77% of the respondents expressed a willingness to drink reclaimed water.

Three of the studies [83,84,87] found a positive relationship between need and attitude toward drinking reclaimed water. Respondents who believed that there was a need for water supply augmentation were more favorable toward the use of reclaimed water for drinking. A positive relationship was also found in three studies [83,86,87] between belief in the adequacy of efficiency of technology and attitude toward drinking reclaimed water. Respondents who believed pollution was serious and widespread were also more favorable toward drinking reclaimed water.

A 1972 study [83] of 972 respondents in 10 communities in California obtained information pertaining to both low- and high-order types of reuse. The strongest opposition--approximately 56%--was directed at the use of reclaimed water for drinking and food preparation. The lowest level of opposition--approximately 1%-- was directed at irrigation of freeway greenbelts and road construction. Thus, it is apparent that the extent of opposition is correlated with the likelihood or extent of close personal contact. Psychological repugnance and concern over purity were most frequently mentioned as reasons for stated opposition. The results of that study did not indicate that cost of treatment was an important determinant of opposition to the use of reclaimed water.

During the recent drought in California, a mail survey was conducted in Irvine, California, a community that uses reclaimed water for a multitude of purposes. Reclaimed water is used for golf course, park, schoolyard, orchard, food crop, and common-area irrigation; common areas include lawns and shrubbery in residential areas that are not under control of the residents. Public awareness of the use of reclaimed water was surprisingly low, for although 58% of the 153 respondents were aware that reclaimed water was used in the city, approximately 75% of the respondents could not identify the source of the irrigation water at the golf course and park [88]. The study further indicated that during drought conditions, respondents were neither willing to pay more for water nor had an interest in water conservation. However, they were willing to accept expanded reclaimed water usages as a means of water augmentation. As in earlier studies, the data indicated that the response of participants was increasingly negative as the proposed uses of reclaimed water were associated more closely with personal contact. Variables that correlated with rejection of reclaimed water were aversion to uncleanliness, aversion to human waste, and over-concern with health.

A 1979 study [89] of 140 Irvine residents indicated that more than 90% of the respondents had favorable attitudes towards using reclaimed water for the irrigation of golf courses, parks, schoolyards, and common areas around residential buildings. Approximately 75% of the respondents had favorable responses toward food crop irrigation, whereas only 28% were in favor of direct potable reuse, a use not occurring (or proposed) at Irvine. During the interviews, the respondents were told that the reclaimed water met all of the DOHS's standards for the existing uses at Irvine. The study included respondents' recommendations regarding future uses for reclaimed water at Irvine. Approximately 56% of the respondents recommended continuation of the existing uses of the reclaimed water, and 5% recommended expansion of the existing uses. Only 5% recommended eliminating existing uses, and almost 25% recommended adding new uses.

Most previous research on public attitudes toward wastewater reclamation dealt with hypothetical uses of reclaimed water that may occur at some unspecified time in the future. A study [90] was undertaken in 1978-79 to assess attitudes toward several wastewater reuse or disposal options actually under consideration for selected communities. This research was necessary to obtain more reliable public responses rather than impersonal projections or speculations. Evaluations of uses ranging from minimal treatment with ocean disposal to tertiary treatment for potable reuse were assessed by the people immediately affected by the options under consideration. Data for this study were obtained by interviewing 140 respondents selected by probability sampling procedures from each of ten California cities. Respondents were presented a detailed analysis of three wastewater treatment and reuse options for their community that covered in a balanced and factual manner the environmental, health, and economic effects of each option. Younger, more affluent, more highly educated respondents who had personally considered the use of reclaimed water had more favorable attitudes than older, less affluent, less-educated respondents who had personally not considered the use of reclaimed water. Further, respondents who believed there was a water supply shortage, that modern technology was capable of treating wastewater, that public health officials would approve certain uses of reclaimed water, and that using reclaimed water would benefit the economy were more favorable in their attitudes.

The results showed that, in general, respondents favored options that protected public health, enhanced the environment, and conserved scarce water resources. For the options assessed in the study, cost did not seem to be an important factor. Options that called for minimal waste treatment and subsequent discharge into the environment without further beneficial reuse were not favored because of environmental and conservation considerations. Options that called for very high degrees of treatment and then use for ingestive purposes were not favored because of the public health considerations. Options that called for high degrees of treatment and then reuse for some beneficial purpose such as agricultural and parkland irrigation were most favored, because they met all three considerations noted.

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CHAPTER 11

LEGAL ASPECTS OF IRRIGATION WITH RECLAIMED WASTEWATER IN CALIFORNIA

Carolyn S. Richardson

INTRODUCTION

As reclaimed wastewater becomes a more significant part of the state water conservation program, legal disputes are likely to arise. The disputes presently foreseeable will come from conflicts over ownership of the reclaimed wastewater and over ambiguities in contractual obligations. Reclamation is a new use of a resource already heavily drawn upon. As water formerly returned to streams after use and treatment is withheld for resale at the treatment site, diminished flow downstream may deprive dependent users of their accustomed supply. Legal action has been taken to block one proposed sale of treated wastewater for this reason [1].

Many existing contracts in California between wastewater reclamation facilities and purchasers do not sufficiently clarify the mutual obligations of the parties. As wastewater reclamation projects have expanded, conflicts have arisen concerning the water entitlements of earlier versus subsequent water users. Although these incidents have been minor, they demonstrate that the best insurance against breach of contract disputes is to clarify the expectations of the parties at the outset. Perhaps more important, the contracts reviewed for this chapter made little provision against liability for personal injury and property damage. Although these hazards may be remote possibilities, they should be addressed in contracts for the sale of reclaimed wastewater; instances of lax compliance with the California Department of Health Services Guidelines have been reported in the past [2].

This chapter focuses on two legal aspects of wastewater reclamation and reuse. The first section discusses the issues of water rights in the ownership and resale of reclaimed wastewater. The second section discusses potential liability and contractual provisions through which exposure to liability may be minimized. As in any area of the law, answers cannot be given with certainty. Until specific legal problems have been addressed by the courts through litigation, or in the legislature through statutes, their solutions can only be stated in probable terms.

STATUTORY PROVISIONS GOVERNING WASTEWATER RECLAMATION

Water Rights in Reclaimed Wastewater

Water rights disputes in the sale of treated wastewater may arise from two sources. The suppliers of raw wastewater may assert an interest in the resale value of the reclaimed wastewater after treatment. Where treated wastewater has customarily been discharged into a stream, downstream water users may assert a right to its continued discharge. As discussed below, recent amendments to the California Water Code have helped resolve the first type of dispute, but the second remains as a potential source of difficulty.

Wastewater treatment facilities have historically operated as wastewater conduits, receiving wastewater from suppliers and discharging it after purification for reuse by others. By reclaiming treated wastewater for direct use in irrigation, a treatment facility abandons this passive role and interrupts the previous reuse cycle. Until recently, the legal means by which a wastewater treatment facility could establish a right to divert wastewater for irrigation were unclear.

Recent changes in the California Water Code, in response to recommendations made by the Governor's Commission to review California Water Rights Law [3], have attempted to resolve these issues of rights to reclaimed water. Unless otherwise provided by agreement, the wastewater treatment facility now has exclusive rights to the treated wastewater as against any supplier of raw wastewater, including suppliers who obtained their water under a water service contract [4]. This concentrates the water rights in the treatment facility, eliminating the need to negotiate with any entity that has contributed to the wastewater. These code amendments make it apparent, however, that the Legislature intended to protect the interests of other legal users who may have established rights to use treated wastewater previously returned to the water system by the treatment facility [5]. The wastewater treatment facility must secure the approval of the

California State Water Resources Control Board (SWRCB) before making any change in the point of discharge or in place or purpose of wastewater use; the Board must review the proposed change to determine that no other legal user will be injured by the withdrawal of water before it may approve the change [6].

Potential injury to downstream users is no obstacle to reclamation in the case of coastal facilities formerly discharging effluent into the sea, or to facilities whose prior land application precluded others from reusing the treated water. In some cases, however, claims of downstream users may raise obstacles to inland facilities previously discharging treated wastewater into streams. A brief review of the system of legal priorities applied to settle conflicts among different water users is helpful to understanding the type of disputes that may arise.

An Overview of California Water Law

California water law is a complex hybrid of different systems. Surface waters are allocated according to rules developed in an uneasy coexistence of riparian and appropriative rights. Groundwater allocation is governed by a system of rights analogous to but distinct from those governing surface waters. In addition, the federal and state water projects create contractual entitlements overlapping the established surface and groundwater rights systems. For our purposes, a brief outline of the two types of surface water rights will suffice to explain water right priorities.

Riparian rights. The riparian water right attaches to land adjacent to a watercourse. The owner of such land may claim a right to use as much of the natural flow of the watercourse as is reasonably necessary to use the land for certain established purposes, among which are household needs, watering domestic stock, and irrigating the riparian property. The significance of this right in the priorities scheme is twofold: it is generally superior to appropriative rights, and it is not extinguished by non-use but can remain dormant endlessly to be asserted when the riparian property is developed. In times of shortage, those holding riparian rights must share the available water among themselves but may defeat the rights of water appropriators entirely [7].

Appropriative Rights. The appropriative water right allows the diversion of water for use on land not bordering a watercourse. This right is not bound to a particular purpose, but it is fixed in amount by the amount claimed at the time of diversion. The water user may change his use or transfer his right so long as the point of diversion and the point of return to the stream are not changed in a manner that interferes with the uses of others. If the amount of water consumed in beneficial use diminishes for five years or more, the right is diminished in quantity and may not be reasserted in its prior amount. Among appropriators, in times of shortage there is no apportioning the loss; a senior appropriator may force a junior appropriator to relinquish his supply [8].

In California, both types of water rights may exist on one stream. There is a long history of litigation determining priorities between riparians and appropriators [9]. The California Constitution was amended in 1928 to impose a prohibition against water waste under either type of right. If a riparian's use is found to be a waste of water, it will not be upheld against the reasonable and beneficial use of an appropriator [10]. However, such a finding is uncommon. The general rule remains that the riparian user making reasonable beneficial use of the water has a right superior to that of the most senior appropriator.

The Permit System. A large obstacle to developing new uses of water is the uncertainty regarding the nature and extent of water rights already existing in a watercourse. California established a permit system in 1914. Before 1914, an appropriation could be made simply by diverting water and putting it to beneficial use; after this date, an appropriation required a permit [11]. The permit procedure is part of the jurisdiction of the SWRCB, which issues permits subject to terms designed to protect existing water rights. The benefit of the permit system is that it brings some degree of certainty and reliability to water supplies, thereby encouraging commercial investment.

An appropriative water right permit has a priority fixed by the date the application is filed, and the amount is recorded [12].

If all rights were within the permit system, greater certainty could be achieved, but not all rights are within the system. The 1914 statute specifically exempted riparian and pre-1914 appropriative rights. Changes or transfers of such rights may be made without notifying the SWRCB [13]. The owner of a post-1914 permit must petition the SWRCB for approval of a change in the point of diversion or in the place or nature of use [14], and the SWRCB may not approve the change if it determines that another legal user will be injured [15]. Although the holder of a pre-1914 right is subject to the common-law prohibition against a change in use that would injure other users, the practice of unrecorded changes very likely has led to an undetected increase in the quantity claimed under these rights over time, while preserving the pre-1914 priority date.

In addition to the unrecorded riparian and appropriative rights, there are at least two other sources of uncertainty: municipal entitlements [16] and state filings [17]. Municipal entitlements enable a municipality to claim a right senior to that of any other user for all amounts necessary to fill its municipal uses [18]. This right expands with the size of the municipality. State filings allow the Department of Water Resources to file claims for unappropriated water needed in a general plan of development. These claims are given a priority date set by the date of filing, but the water is left in the stream until required for development. This creates an apparent availability of water that may later be withdrawn if a permit is granted on a state filing.

Often it cannot be determined with certainty whether there is surplus water in a stream available for appropriation. On the basis of prior studies and hearings on protested applications, the SWRCB believes it can estimate the amount available with some reliability [19]. Since all permits are issued subject to prior rights, any shortages that occur should be borne by the most junior appropriator.

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Rights to Reclaimed Wastewater

As noted previously, a recent amendment to the Water Code provides that the owner of a wastewater treatment facility shall hold the exclusive right to the treated wastewater as against any supplier of water entering the facility, unless there has been an agreement to the contrary. This amendment should reduce the likelihood of disputes that might otherwise arise between wastewater treatment facilities and upstream water users as wastewater reclamation begins to be recognized as a means of producing a valuable commodity.

Unfortunately, the Water Code does not address the possibility of disputes arising between owners of wastewater treatment facilities and downstream water users who may have been relying under their appropriative or riparian rights upon treated wastewater previously released by the treatment facilities. These downstream users may challenge the legal authority of a treatment facility to redirect its return flow when the owner of the facility petitions the SWRCB for approval of the reclamation project, or they may later challenge the priority of the treatment facility's water right when the demand for water exceeds the supply. The SWRCB cannot approve a proposed reclamation use if it finds that any legal user will be injured (text, page 11-3, note 6). Despite having obtained approval at the outset, however, the treatment facility may lose its water to future challengers unless it has demonstrable evidence that it has a right to divert the amount of water it reclaims, and that this water right predates the rights of the challengers. Ordinarily, such evidence is provided by a permit to appropriate water.

The new provisions in the Water Code do not require the owner of a treatment facility to obtain an appropriative water right before diverting return flow for reclamation: instead, the owner is allowed to petition the SWRCB for approval of a "change in point of discharge, place of use or purpose of use of treated wastewater." The code states that the Board shall review the proposed changes pursuant to the provisions applicable to changes in point of diversion, place of use, or purpose of use under an appropriative permit [20], a procedure that can be simpler than that required to obtain a new appropriative right.

The legal effect of obtaining Board approval for a new use of reclaimed wastewater under this change petition procedure is unclear. The fact that the Legislature provided this procedure and did not direct the owner of the treatment facility to apply for an appropriation permit may indicate that it intended to encourage reclamation by establishing a new means of obtaining a right to divert and use water. The hazard for the wastewater treatment facility relying on this new statutory procedure is that in simply directing the SWRCB to review reclamation change petitions under a procedure originally designed for changes under existing appropriation permits, the Legislature did not provide a means for establishing a priority date or quantity for the new reclamation use. Moreover, the Legislature did not state that water approved for reclamation under this procedure would no longer be available for appropriation by others. These uncertainties may leave the wastewater treatment facility open to future challenges, even though it has obtained Board approval to reclaim water under a petition for change.

In most cases, the procedural burden of obtaining approval of a change petition will not differ significantly from that of obtaining an appropriation permit. Under both procedures, the applicant must give notice: usually actual notice to known water users, and publication in the affected locale. Under both procedures, the Board must examine the effect of the proposed reclamation use on other lawful users of water and conduct a public hearing on any unresolved protests. Depending upon the magnitude of the proposed reclamation project and the complexity of local water rights issues, the wastewater treatment facility owner may find that the change petition procedure offers no significant short-cut to approval [21].

In view of these procedural similarities and in view of the greater certainty represented by a permit to appropriate water, in most instances it will be advisable for the owner of a wastewater treatment facility to file an application and obtain an appropriation permit before diverting treated wastewater for reclamation. It is particularly important to consider an application for an appropriation permit if substantial investments will be made, or if the proposed reclamation will divert water that historically has been returned to the stream for reuse by others. An application form is found at Appendix C.

Parallel Service Statutes

The treatment facility desiring to sell its reclaimed wastewater may be liable to pay compensation to established suppliers of fresh water under the "parallel service statutes" [22]. These statutes were originally enacted in 1915 to protect the investment of private utilities from later competition by public entities but have since been expanded to protect established public entity suppliers from encroachment by private utilities [23]. Under the parallel service statutes, an established fresh-water supplier is entitled to demand compensation to the extent that it is damaged by any of its water service facilities being made inoperative, reduced in value, or rendered useless to it as the result of a competing water supplier entering its service area [24].

The sale of treated wastewater may be considered a competing service under these statutes. The Health and Safety Code prohibits sewage districts from supplying treated wastewater within the water service area of a city, water district, or other local agency without its consent [25]. Fresh-water suppliers are interpreting this provision as enabling them to demand compensation for any facilities already serving the sites where reclaimed wastewater is to be applied [26].

The effect of the parallel service statutes may be to discourage the sale of reclaimed wastewater by parties who are not established suppliers of fresh water. Most localities where treated wastewater could be sold for landscape irrigation are within the service area of a fresh-water supplier [27]. Applying these protective statutes to require compensation from reclaimed water providers under these circumstances, however, conflicts with the state policy promoting the use of reclaimed water for greenbelt irrigation [28]. Furthermore, restrictions on the use of such water should prevent its sale from appreciably undercutting the rate base of an established fresh-water supplier. For these reasons, the applicability of the parallel service statutes to the sale of reclaimed wastewater for landscape irrigation is questionable, and if compensation to fresh-water suppliers is required, the amount may be minimal.

Nonetheless, it is advisable to consult at the outset with all fresh-water suppliers serving the target application area to determine whether there may be any parallel service difficulties. One example of an accommodation between a reclaimed water purveyor and a supplier of fresh water is the arrangement between the Walnut Valley Water District (WVWD) and the Rowland Area County Water District (Rowland). A copy of a Memorandum of Understanding between WVWD and Rowland is found at Appendix D. When WVWD transports reclaimed wastewater into the service area of Rowland, the districts negotiate a paper sale of the water. Rowland then bills customers within its service area and remits the wholesale price to WVWD. The reclaimed water remains in WVWD pipes until it reaches the ultimate user. Under this arrangement, the supplier of the reclaimed water retains physical control over the water, while the local fresh-water supplier retains control over pricing in its district [29].

The effect of parallel service statutes on wastewater reclamation projects will vary considerably with the circumstances of each case. Wherever the proposed use of reclaimed water will be within the service area of an established fresh-water supplier, the reclaimed-water purveyor should give early consideration as to how potential disputes can be resolved.

THE WASTEWATER SUPPLY CONTRACT: PROVIDING AGAINST LIABILITY FOR PERSONAL INJURY AND PROPERTY DAMAGE

The purpose of including a discussion of limiting exposure to liability by contract is not to equip the reader to draft contracts, but merely to acquaint the reader with the complexity of this field. As noted previously, a number of wastewater supply contracts reviewed by this author made little attempt to allocate liability for personal injury or property damage. This discussion is therefore included both to caution the reader and to prepare the reader for an informed consultation with insurers and legal counsel.

This section will begin with an overview of the legal theories by which claimants may attempt to attach liability to wastewater reclamation projects. No treatment of liability in commercial activities involving public entities may omit a discussion of governmental liability; the narrow protection offered through immunity will therefore be explained. The focus of this section, however, will be upon the scope of liability limitation that may be achieved by contract [30]. A sample of proven liability disclaimer and limitation clauses adapted to the wastewater supply contract is provided in Appendix E.

Several types of liability must be considered in the contractual stage. The claims that concern us are claims for personal injury and property damage due to contamination by reclaimed wastewater. The risk to the irrigator of short-term crop damage is fairly well understood and for this reason can be provided for by contract between the buyer and seller. The potential for injury to third parties is less well understood and less easily dealt with by contract. No adverse health effects have been reported, although there are over 200 wastewater reclamation projects in California, some long established. However, even the remote possibility of mismanagement in effluent application, malfunction in treatment [31], and toxic chemical contamination due to industrial chemical spills or dumping raises a realistic concern that a third party personal injury or property damage claim may be brought against some wastewater facility [32].

Proof of damage to the claimant and of a causal connection to the activities of the party to be held responsible are prerequisites to a successful suit. For some types of damage associated with wastewater reclamation the proof may be relatively simple, as where reclaimed wastewater comes into contact with a crop on which its use is not approved. In such a case, the owner may suffer an immediate loss of marketability. Generally the association between observed damage and the use of reclaimed wastewater for irrigation will be difficult to establish. However, there is no room for complacency. A similar problem of proof exists in establishing damages due to personal exposure to environmental hazards in the workplace and due to the ingestion of slow-acting medicinal toxins. The law developing in these areas suggests a trend toward relaxing some of the traditional obstacles barring recovery. Courts show an increasing reluctance to bar suits because of statutes of limitation, and an increasing willingness to infer responsibility for damage by means of circumstantial evidence [33]. We will assume that our hypothetical claimants are able to prove actual damage causally connected to the use of reclaimed wastewater for irrigation.

Legal Theories Supporting Liability in the Sale of Treated Wastewater

Negligence

A person is negligent when he fails to take those precautions a reasonable person would take to protect others from foreseeable risks arising from his activities. The violation of a statute or administrative regulation designed to protect against a particular risk of harm raises a presumption of negligence and exposes the violater to liability for any injuries to a member of the class intended to be protected [34]. If any of the quality criteria or management regulations are violated in the treatment, delivery, or application of reclaimed wastewater, negligence would be presumed. Violation of the treatment standards would raise a presumption of negligence against the wastewater treatment facility. Violation of management standards in the application of the water would raise a presumption only against the irrigator, unless the treatment facility had violated a specific duty to inspect the irrigation operation [35] or was negligent in entrusting the wastewater to this operation. The statutory standard is no more than a minimum; the wastewater treatment facility may still be negligent if special circumstances raise foreseeable dangers beyond those provided for in the standard. An example of special circumstances might be unusual subsoil characteristics at the irrigation site that make surface irrigation inadvisable because of the risk of polluting groundwater.

Strict Liability in Tort

Anyone injured by a defective product may hold the manufacturer and all parties engaged in putting the product on the market strictly liable for his injury [36]. No proof of negligence or other wrong-doing is required [37]. This product liability theory recognizes two types of product defect: manufacturing defects and design defects. A manufacturing defect in treated wastewater might be found if it failed to meet the regulatory water-quality standards; a design defect might be found if water that met all applicable water-quality standards nonetheless caused damage, as by residual salt concentration or boron toxicity [38].

Strict liability applies only to the manufacture of goods. It is not imposed upon businesses providing services in which defective goods may incidentally be employed. No case has been reported characterizing reclaimed wastewater, but because a wastewater reclamation facility processes and sells the water for commercial use by others, it is more likely to be found a manufacturer of goods than a mere provider of services [39].

Warranty

If wastewater is considered a commercial good, then injured parties may hold wastewater suppliers liable for breach of warranty [40]. There is some opinion that structuring the supply contract as a lease instead of a sale will avoid warranty liability. This is questionable. A court is free to look to the real character of a transaction; where it finds that the product "leased" is consumed, it is unlikely to allow this subterfuge [41].

A sure prevention of warranty liability is to limit the number of warranties provided. Unfortunately for the supplier, warranties are more easily created than avoided. Any sample, model, or description of the goods will create an express warranty. The state's wastewater Reclamation Criteria and Regional Water Quality Control Board requirements, as well as any informal assurances of safety, would be considered express warranties of quality [42]. Moreover, the law will imply certain warranties without any specific representations by the seller, such as the implied warranty of merchantability [43] and the implied warranty of fitness for a particular purpose.

The implied warranty of fitness for a particular purpose is of special concern in irrigation with reclaimed wastewater. It arises when the seller has reason to know that the buyer intends to use the goods for a particular purpose, and that the buyer is relying on the seller's skill and judgment to furnish suitable goods. An implied warranty of fitness for the known intended use would arise in every wastewater supply contract because of the necessarily detailed knowledge of the buyer's use and because of the active role in advising the buyer which is imposed by law upon the treatment facility.

Although anyone damaged by breach of express warranty may sue the seller, breach of an implied warranty may only be asserted by the party with whom the contract was made [44]. By complying with certain formalities, the seller in commercial transactions has considerable room to reduce exposure to both kinds of warrant liability.

Governmental Immunity

Where wastewater reclamation is conducted by public entities, the liabilities of the preceding section are subject to procedural limitations and immunities found under the California Tort Claims Act [45]. The Act provides that public entities are not liable for injuries except as permitted by statute [46]. Most of this immunity is then withdrawn. Public entities are fully liable in suits based upon contract [47] or workers' compensation [48]. The following governmental immunities are limited to personal injury and property damage claims not based upon contract.

Liability From Inadequacy of Standards

Public entities and their employees are immune from liability for any injury resulting from the adoption, non-adoption, or failure to enforce any statute or regulation. The state and the Department of Health Services cannot be held liable if the wastewater treatment standards prove insufficiently rigorous. It has been speculated that this immunity may also shield entities directly involved in wastewater reclamation from liability for failure to enforce those standards [49]. This is unlikely, as the California Supreme Court has ruled that this statutory immunity is confined to quasi-legislative and law enforcement agencies. It is specifically withheld from public entities which are charged by law with a regulatory duty designed to protect the public against particular injuries [50]. A public licensing entity which must require compliance with certain health and safety regulations will be liable if it grants approval to applicants who do not meet the regulatory standards [51]. Similarly, an entity charged with a specific duty of ongoing regulation will be liable if it fails to regulate.

Liability From Failure to Inspect

Public entities and their employees are generally immune from liability for injuries resulting from a failure to inspect any property to determine if the property meets applicable safety statutes [52]. A public reclamation entity should not be liable for failure to detect unsafe conditions that arise after the approval of a private irrigation site. This immunity would be overridden, however, by a specific statutory duty to inspect.

Liability From the Acts of Employees

Public entities may be vicariously liable for the acts of their employees except where the employees themselves are immune [53]. Generally, public employees are liable to the same extent as private employees [54], but the Tort Claims Act immunizes them when they must exercise discretion. The scope of this immunity is not large. It is confined to policy-making decisions involving a conscious weighing of the risks and advantages of a particular course of action [55]. Furthermore, immunity only extends to injuries that are a direct result of the decision; actions taken to implement it are not shielded. As an illustration, the decision that a particular type of irrigation can be done safely with treated wastewater would clearly be discretionary. The decision that a particular irrigation site could use treated wastewater safely may also be discretionary. Lower-level decisions and activity in actually providing the wastewater to the site would not be immune from liability. Discretionary immunity covers plans and designs for construction or improvement to public property [56]. This would bar suits based on faulty wastewater treatment plant design, not suits based on negligent use or maintenance.

The role of governmental immunity in preventing liability for injuries caused by irrigation with treated wastewater is very restricted. In actions based on contract it is nonexistent. For most situations, the public entity will be as exposed to liability as a private entity.

Procedural Limitations to Public Entity Liability

The more significant protection offered by the Tort Claims Act is found in its requirement that no claim may be pursued in court unless it has first been presented to the appropriate public entity [57]. Many claims are settled or dropped at this stage. The Act also shortens the time for bringing a claim. Claims for personal injury, property damage, or damage to growing crops must be filed within one hundred days after the claim accrues, as opposed to a one-year filing period for suits against private defendants. Other claims, including contract claims, must be filed within one year, whereas in private actions, suits based on contract have a four-year period [58].

Contractual Limitation of Liability

Negligence

The supply contract can minimize the treatment facility's exposure to negligence claims. It does this by clarifying the division of management responsibilities between the parties in the contract and by preserving evidence that the user was fully instructed in all regulatory requirements. The treatment facility must bear all liability resulting from negligence in meeting the treatment standards [59], but the contract can insulate it from risks related to the management of on-site application by specifying the operations and facilities that are under the exclusive control of the user. Most of the contracts reviewed in preparing this material divided responsibilities with satisfactory specificity. A few contracts stated particular off-site contamination risks and set forth management practices required to minimize these risks [60]. Many contracts appended the Health Services Guidelines and the requirements of the Regional Water Quality Control Board to the contract and incorporated them, by reference, into the provisions listing the user's responsibilities. This is recommended.

Strict Liability in Tort

Two defenses to this form of liability will be mentioned here, because they must be prepared in the reclaimed-wastewater-supply contract: the defenses of misuse and express assumption of the risk.

Misuse. A manufacturer is not responsible for damages resulting from unintended, unforeseeable, and abnormal use of his product. Courts are more likely to absolve a manufacturer from liability for the misuse of his product if the proper use is spelled out in the sale contract [61]. The wastewater supplier's duty to instruct the user should be satisfied by attaching the appropriate regulatory guidelines to the contract and specifying any additional management practices necessitated by particular hazards associated with the proposed site, manner of application, or crop.

Assumption of the risk. A manufacturer is not responsible for damage resulting from risks assumed by the buyer. Statute forbids assuming the risk of noncompliance with standards imposed by law upon the facility [62], but the risk of what we have termed design defects (damaging qualities in water that meets all regulatory standards) may be assumed. This is a limited defense. It does not prevent recovery by third parties injured by the defect. It does not cover unknown hazards; the buyer must have knowledge of the particular risk, understand the magnitude of the risk, and voluntarily assume it [63].

A buyer who signs a contract containing a broad statement that he agrees to assume all risks and accept all liability will probably not be found to have assumed the particular risk that resulted in damage. If the supplier wishes to avoid liability for design defects by an assumption clause, all risks known to be associated with the chemical composition of the effluent supply and the proposed crop should be stated in the contract and referred to in the assumption clause so that it is clear that the buyer expressly assumes those risks [64].

Warranty

The California Commercial Code allows sellers to limit their liability for breach of warranty by disclaiming, modifying, or excluding warranties [65] and by limiting the remedies available upon breach [66].

Disclaimer. Unintended oral warranties as well as implied warranties may be disclaimed in the supply contract. The term "merchantability" must be used to disclaim the implied warranty of merchantability [67], but otherwise no particular language is required; unintended oral warranties and implied warranties of fitness for a particular purpose may be excluded in most contracts if the contract merely states, "There are no warranties that extend beyond the description on the face of this contract" [68].

However, for any disclaimer to be upheld against the buyer there must be no question that it was brought to his attention. Courts enforce this requirement of conspicuousness with zeal. To disclaim the implied warranties, a disclaimer must be set out from the contract in bold-face type or markedly contrasting color [69]. Furthermore, mere notification of a broadly worded disclaimer will not suffice unless the buyer understands the nature of the risk he will incur [70]. Because the processing of wastewater for use in irrigation is highly technical, requires compliance with a complex body of regulations, and involves subtle potential for damage not likely to be foreseen by the businessman-farmer, disclaimers in these contracts are particularly susceptible to judicial disapproval. Care must be taken to notify the buyer of the scope and import of any warranty disclaimer. Any doubt will be resolved against the seller.

Some warranties may not be disclaimed. Compliance with regulatory wastewater-quality standards is probably an undisclaimable warranty [71].

Limitation of remedies. The Commercial Code allows sellers to reduce their exposure to liability for breach of warranty by specifying the remedies available to the buyer [72]. Courts do not view the limitation of remedies with the disfavor shown disclaimers, possibly because the seller appears to be promising some remedy rather than avoiding all remedy. The public policy against disclaiming warranties created by law does not apply to limiting remedies for the breach of such warranties [73]. The code does give the buyer some protection. The remedy provided in the contract will be optional unless the contract states that it is to be exclusive; moreover, even an "exclusive" remedy will be treated as optional unless it gives the buyer the substantial value of his bargain [74]. The tolerance of the courts to the repair or replace remedy in the sale of consumer goods, where courts otherwise have been protective of the buyer, indicates this substantial value requirement is not a great obstacle [75]. A truly bargained limitation can allow the parties to achieve an approximation of a fair sharing of the unknown risks in their business relationship. The parties who know the commercial context must determine what is reasonable.

The contract may also limit the time period in which a claim may be brought to court by the buyer. The statute of limitations for warranty actions against private defendants is four years under the commercial code, but it may be shortened by agreement to one year [76]. Because any crop damage suffered by the buyer should be apparent at the end of one growing season, providing a one-year statute of limitations should be fair to the buyer, yet would protect sellers against stale claims upon past damages for which rebuttal evidence would not be available [77].

Indemnification

The wastewater reclamation facility may reduce its exposure to liability in the supply contract, but it cannot altogether eliminate it. The preceding contractual devices can bar or limit many claims that might be asserted by the buyer. They are less effective obstacles to third-party claims [78]. Bearing primary liability does not require paying damages, however. The wastewater supplier may require in the contract that the water user indemnify it against third-party liability [79]. An agreement to indemnify is an agreement by one contracting party to pay claims brought against the other party. The parties may agree to indemnification against some or all hazards. They may even provide for indemnification against damages resulting from negligent violations of law [80], such as failure to meet the regulatory water-quality standards, but such an agreement must be explicit, because any doubt will be resolved against the supplier [81].

The ability of the water supplier to avoid payment of damage claims by indemnification depends upon the ability of the water user to pay and upon the enforceability of the indemnity clause. An agreement to indemnify is a contract between potential defendants. It does not limit the recovery of the injured party. If the water user is unable to pay, the water supplier will be responsible for the full amount of the claim. For this reason, it is essential to make the wastewater supply contract contingent upon the water user obtaining adequate insurance. The enforceability of an indemnification clause will depend upon the general principles of contract law discussed in the next section.

Public Policy Restraints on Avoiding Liability by Contract

Certain formal rules restraining liability avoidance through the contractual devices of assumption of risk, warranty disclaimer, and indemnification have been mentioned. These are: the rule requiring actual notice to the buyer by conspicuous and clear language, the rule requiring understanding assent by the buyer, and the rule requiring terms by which the buyer accepts liability to be interpreted strictly against the seller. In addition, there is a general principle of protection against unfair dealing which will invalidate many provisions limiting liability that are formally correct.

Under the common law doctrine of unconscionability, a court may refuse to enforce a contract in which there was an absence of meaningful choice for one of the parties, coupled with terms unreasonably favorable to the other party [82]. The Uniform Commercial Code explicitly adopted this common law rule; the California Commercial Code did not. The status of the doctrine in the enforcement of commercial contracts in California is therefore uncertain. While not basing their decisions upon unconscionability, California courts have frequently mentioned the doctrine as an alternate ground of decision when they have struck down terms "oppressive" to the buyer. It appears that the doctrine is alive and well beneath the surface of these decisions and should inhibit any seller from attempting to impose terms too one-sided to his benefit [83].

Courts are particularly protective of the buyer when they determine that the sales contract is an adhesion contract. An adhesion contract is one in which the buyer has little opportunity to bargain for favorable terms. This situation typically arises when a buyer has a need for particular goods and limited ability to seek an alternative supply, or when all the sellers in the market for those goods rely on similar contracts. When an adhesion contract is found, the courts will scrutinize any clause shifting liability to the buyer to determine whether the buyer gave understanding and voluntary assent. Courts have refused to enforce provisions unquestionably brought to the buyer's attention when they have determined that there was little opportunity for real bargaining and that the provisions defeated the reasonable expections of the buyer [84].

A contract for the sale of reclaimed wastewater, at least to agricultural irrigators, may have some of the ingredients of adhesion: the goods sold may be a commercial necessity in water-short times, and supply may be so limited geographically that the buyer has little ability to shop. Although the present abundance of fresh water as an alternative supply argues against adhesion, it is prudent to bear in mind the possibility of this interpretation; care should be taken to preserve in the contract some evidence of understanding bargaining over the terms allocating financial responsibility for damages to the buyer.

Conclusion

One writer has suggested that a wastewater supply contract most likely to minimize the possibility of future third-party liability is one that allocates financial responsibility according to the control of each party over the potential source of damage. The theory is that financial responsibility is necessary to promote caution. Under such a contract, all risks associated with wastewater treatment and with delivery to the user's headgate would be borne by the water supplier. All risks associated with the proper application of the water after delivery would be borne by the water user. To make the obligations of each party clear, the contract would specify all regulatory guidelines appropriate for the proposed use [85]. To achieve the separation of liability, express warranties, disclaimers of warranty, and assumptions of risk would be employed to bar claims by each party for damage resulting from elements within his control. Cross-indemnification agreements would similarly allocate responsibility for insuring against liability toward third parties. This is the approach apparently preferred by the few supply contracts reviewed that dealt with liability in some detail [86]. It has much to recommend it.

In some other enterprises, however, the apportionment of liability is treated solely as a matter of economics; the price of the product bears the cost of insuring against its hazards. A rational goal under this approach is to concentrate the cost of insurance upon the buyer to the extent that it can be done and preserve the competitiveness of the product. This section concludes by reviewing the devices by which the obligations of the seller toward the buyer can be clarified, the liability toward the buyer can be minimized, and the responsibility for insuring against third-party liability can be concentrated on the buyer.

To minimize points of litigation between the parties to the contract, all warranties intended should be expressed in writing. The statutory wastewater treatment standards are certain to be among these. All other warranties should be disclaimed as required by the Commercial Code: in writing and conspicuously. It is prudent to have the buyer initial the disclaimers. Particular mention should be made of any known and unavoidable risks. The buyer should expressly assume these.

The parties should also agree upon a limited remedy in the event a warranty is breached. For private water suppliers, a separate clause should be included limiting the time within which an action for breach of warranty may be brought, not less than one year from breach.

If the supplier wants to concentrate all responsibility for insuring against third-party liability on the buyer, the contract should provide that the buyer agrees to indemnify the supplier against any and all liability arising from the use of treated wastewater for irrigation. It should specifically state that the buyer will indemnify the supplier even if the cause of damage is active negligence by the supplier. The contract should provide that it is the obligation of the buyer to obtain insurance; it should be contingent upon proof of insurance.

The goal of a contract is to keep the parties out of court. This is most likely to be achieved when the obligations of the parties are clearly understood and when there is a sense of fair dealing. These are also the most important factors in determining whether a contract will be enforced in court. Whether it is reasonable, fair, or advisable to impose the burden of financial responsibility upon the buyer to the fullest extent possible depends upon the economic circumstances surrounding the particular wastewater supply contract. A very different allocation may be advised. It is certain, though, that if the risks are not realistically appraised and bargained for to preserve the reasonable expectations of the parties, the contract will be rewritten in court.

NOTES

1. People v. City of Roseville, Civil No. 49608, Cal. Super. Ct., Placer County, Sept. 30, 1977. The City of Roseville contracted to sell treated wastewater to certain irrigators in the drought year of 1977. For many years it had released its effluent into Dry Creek after treatment. The SWRCB brought an action to enjoin the sale because the withdrawal of the water would injure other legal users downstream.
2. Ling, C. 1978. Wastewater Reclamation Facilities-Survey 1978. Sanitary Engineering Section, Department of Health Services, Berkeley, Calif.
3. Governor's Commission to Review California Water Rights Law, final report, at 63-65 (December, 1978).
4. Cal. Water Code Section 1210 (West Supp., 1984).
5. Cal. Water Code Section 1210 (West Supp., 1984).
6. Cal. Water Code Section 1211 (West. Supp., 1984), Section 1700 *et seq* (West, 1971). By approving the diversion of the treated wastewater under this procedure, the SWRCB is not granting the treatment facility an appropriation permit. For the difficulties that may result from using this abbreviated procedure instead of applying for an appropriation permit, see ensuing discussion under Rights to Reclaimed Water.
7. A riparian right may be quantified and given a priority date in a statutory adjudication proceeding. This time-consuming and expensive process has only been accomplished for a few small stream courses. See Cal. Water Code Sections 2500 *et seq* (West, 1971; West Supp., 1984).
8. No more than a skeletal treatment of these water rights can be given here. For a thorough yet reasonably concise study, the reader is referred to the reports issued by the Governor's Commission to Review California Water Rights Law (published May, 1977-January, 1978).
9. The definitive cases establishing the priority of riparian over appropriative rights are Lux v. Haggin, 69 Cal. 255, 10 P. 674 (1886); Herminghaus v. S. Cal. Edison Co., 200 Cal. 81, 252 P. 609 (1926).

10. Joslin v. Marin Municipal Water Dist., 67 Cal. 2d 132, 429 P. 2d 889, 60 Cal. Rptr. 377 (1967).
11. A 1923 amendment to the Water Code made the permit system the exclusive means of obtaining a water right.
12. Cal. Water Code Section 1201 (West, 1971). For permit procedure see Title 23, Cal. Admin. Code, Chapter 3, Subchapter 2.
13. Cal. Water Code Section 5101 (West Supp., 1981).
14. Cal. Water Code Section 1701 (West, 1971).
15. Cal. Water Code Section 1702 (West, 1971).
16. Cal. Water Code Sections 106.5, 1203, 1460-1464 (West, 1971).
17. Cal. Water Code Section 10500 (West Supp., 1984).
18. Cal. Water Code Section 1460 (West, 1971): a municipal use is the use of water for the municipality or its inhabitants for domestic purposes. See also 23 Cal. Admin. Code Section 664 (Oct. 13, 1979), Municipal Uses, and 23 Cal. Admin. Code Section 661, Domestic Uses. Under Cal. Water Code Section 1463 (West, 1971), a municipality is allowed to appropriate an amount of water beyond its present municipal needs, provided that others may obtain temporary rights to the surplus. When the municipality expands its water consumption, it must compensate those temporary users for facilities rendered valueless by the withdrawal of water. In addition to this statutory municipal right, there is a common-law municipal right which may be asserted by former Spanish pueblos. Because of its limited applicability, it is not discussed in this chapter.
19. Telephone interview with Carol Atherton, Assistant Chief, Division of Water Rights, State Water Resources Control Board (March 23, 1982).
20. Cal. Water Code Sections 1210 to 1211 (West Supp., 1984); Cal. Water Code Sections 1700 et seq. (West, 1971).
21. The procedure for obtaining an appropriation permit is set forth at Cal. Water Code Sections 1300 et seq (West, 1971). The major differences in procedural burden between the two options are in the requirements of the application and notice. The permit application generally requires more information than the change petition (including maps and drawings of the proposed diversion).

Whereas a notice procedure is prescribed by statute for a permit application, the Board has discretion under the change procedure to enlarge or attenuate notice. Those differences will disappear where it is apparent to the Board from the size of the proposed reclamation project, or from the particular circumstances of the reclamation locale, that other water users are likely to be affected. Moreover, if protests are filed against a change petition, there will probably be no savings in time to recommend the change petition over a permit application.

22. Stats. 1915, c. 91, now Cal. Pub. Util. Code Section 1501 et seq, (West, 1975).
23. Cal. Pub. Util. Code Sections 1505, 1505.5 (West, 1975). Under another recent amendment to the Water Code, public utilities are prohibited from supplying water to any land within a municipal water district subject to indebtedness for water bonds, as long as the district is ready, willing and able to serve the land, unless a majority of the voters consent at a special municipal water district election. Cal. Water Code Section 71699 (West Supp., 1981). This appears to prevent the sale of water even if the municipal entity consents. This restriction might be circumvented if the municipal entity resolves that it is not "ready, willing and able" to serve the target area.
24. Cal. Pub. Util. Code Section 1503 (West, 1975).
25. Cal. Pub. Con. Code Section 20802 (West, 1984).
26. It may be argued that the placement of this provision in the Health and Safety Code, under the powers of sanitary districts, indicates that the legislature was concerned with assuring an uncontaminated water supply, not with restraining wastewater competition. The provision does not state that compensation may be a condition to consent, nor does it refer to those sections of the Public Utility Code requiring compensation.
27. The experience of the Carmel Sanitary District demonstrates that this problem is not merely theoretical. CSD has contracted to supply treated wastewater to golf courses within the service area of the Cal American Water Company. Cal American raised vigorous objection to the contracts, asserting that it has facilities that

will go unused if treated wastewater is supplied. Negotiations were suspended pending grant approval for the CSD project at the date of this writing. Interview with Mike Zambory, General Manager, Carmel Sanitary District (March 25, 1982; April 13, 1983).

28. Cal. Water Code Section 13550 (West, Supp. 1984): "The Legislature hereby finds and declares that the use of potable domestic water for the irrigation of greenbelt areas, including, but not limited to, cemeteries, golf courses, parks, and highway landscaped areas, is a waste or an unreasonable use of such water...when reclaimed water... is available..."
29. Interview with Richard Mills, Water Resources Control Engineer, Office of Water Recycling (March 9, 1982).
30. See Brown, E. C., and N. Weinstock, Legal Issues in Implementing Water Reuse in California, 9 Ecology Law Quarterly 243, 278-292, for a more extensive discussion of the applicability of these theories of liability to wastewater reclamation projects.
31. See note 2. Ling, C. Wastewater Reclamation Facilities Survey 1978.
32. The safety record of reclamation projects is excellent. Based on this record, casualty underwriters consider the risk of third party claims to be low; irrigators have not reported difficulty in expanding their insurance coverage to include these risks. It is not the purpose of this chapter to spread alarm, but to add by contractual foresight to the margin of safety already created by sound reclamation practices.
33. Sokol, M., Statutes of Limitations and Pollutant Injuries: The need for a Contemporary Legal Response to Contemporary Technological Failure, 9 Hofstra L. Rev. 1525 (1981). *Res ipsa loquitur* is the theory of proof which legal theorists propose to apply to overcome the difficulty of determining the responsibility of individual sources in pollution injury suits. It is codified in Cal. Evid. Code Section 646 (West Supp., 1984). Under this theory, a presumption of negligence is raised whenever it can be concluded that a particular accident would not occur without negligence by someone and that the defendant is probably

the one responsible. It is undergoing rapid expansion in the field of medical products liability, where it has been used to attach liability to entire sectors of the pharmaceutical industry. Sindell v. Abbott Laboratories, 26 Cal. 3d 588, 607 P. 2d 924, 163 Cal. Rptr. 132 (1980) (liability of manufacturers of diethylstilbesterol). It may not be expanded to wastewater reclamation, however, for two reasons: it has traditionally been considered inapplicable to new industries because not enough is known about hazards of non-negligent operation; it is questionable in wastewater reclamation because of the number of factors that could lead to contamination despite due care. See Brown and Weinstock, Legal Issues, supra, note 30, for citation of cases in which res ipsa loquitur was used to establish negligence in the supply of fresh water.

34. Byrne v. City and County of San Francisco, 113 Cal. App. 3d 731, 170 Cal. Rptr. 302 (1980); Vesely v. Sager, 5 Cal. 3d 153, 486 P. 2d 151, 95 Cal. Rptr. 623 (1971).

35. See discussion under govenmental immunity. In general, negligent inspection of property does not give rise to liability against public entities.

36. Recovery may be obtained not only for personal injuries but also for injuries to property alone, such as crop damage. Purely economic injury, such as loss of bargain due to the reduced value of the water, is not recoverable under this theory. Seely v. White Motor Co., 63 Cal. 2d 9, 19, 403 P.2d 145, 45 Cal. Rptr. 17 (1965); Gherna v. Ford Motor Co., 246 Cal. App. 2d 639, 649, 55 Cal. Rptr. 94 (1965); Elmore v. American Motors Corp., 70 Cal. 3d 578, 451 P.2d 84, 75 Cal. Rptr. 652 (1969).

37. Greenman v. Yuba Power Products, 59 Cal. 2d 57, 377 P.2d 897, 27 Cal. Rptr. 697 (1963).

38. In determining whether a design is defective, the benefits of the design are weighed against the risk of harm it presents. Barker v. Lull Engineering Co., 20 Cal.3d 413, 573 P.2d 443, 143 Cal. Rptr. 225 (1978). Because properly produced wastewater creates economic benefits that should outweigh the cost of isolated instances of damage, it is possible that courts would

not find its "design" defective; in this case, strict liability would not be applied. Negligence and warranty theories remain. A third type of product "defect" is being introduced into strict products liability from the law of negligence, through a combination of medical malpractice and product liability. Under this theory, a product (such as a drug) that is not defective in either manufacture or design may still be deemed defective because of a failure to give adequate warning of potential hazards. Fogo v. Cutter Laboratories, Inc., 68 Cal. App. 3d 744, 137 Cal. Rptr. 417 (1977). This is conceivably applicable to the sale of reclaimed wastewater. The Health Services Guidelines should satisfy any requirement of adequate direction and warning, however.

39. Reclaimed wastewater may have been deemed a "good" for the purposes of warranty law. See below, note 40, Voth v. Wasco Public Utility District.

40. Fogo v. Cutter Laboratories, Inc., supra, 68 Cal. App. 3d 744, note 38. Warranty law is governed primarily by the California Commercial Code, Sections 2312-2317 (West, 1964). The definition of goods in the code does not preclude wastewater (Section 2105: "all things moveable at the time of identification to the contract for sale..."), but there is no definitive court decision. One case appears to accept the applicability of warranty theory to a claim for wastewater damage to crops, but the issue was not directly decided by the court. Voth v. Wasco Public Utility District, 56 Cal. App. 3d 353, 128 Cal. Rptr. 608 (1976).

41. Voth v. Wasco Public Utility District, supra, 56 Cal. App. 3d 353, note 40, at 359, indicates that reclaimed wastewater supplied as part of the lease of a wastewater treatment district's land would be subject to the warranty provisions of the code.

42. It is not necessary for the buyer to have relied upon these assurances as the basis of the bargain. Any representation of fact by the seller becomes woven into the "fabric of the agreement." Hauter v. Zogarts, 14 Cal.3d 104, 115, 534 P.2d 377, 120 Cal. Rptr. 681 (1975).

43. The implied warranty of merchantability arises when the seller is a merchant dealing in goods of the kind sold by the contract in question. There is little doubt that if reclaimed wastewater is a good, the facility selling it will be deemed a merchant. See Brown and Weinstock, Legal Issues, supra, note 30, at 282. This warranty is violated if the reclaimed wastewater is not fit for the ordinary purposes of irrigation. Wastewater that meets the regulatory quality standards should satisfy the warranty of merchantability.
44. Hauter v. Zogarts, supra, 14 Cal. 3d 104, note 42, at 119-120.
45. Cal. Gov. Code Sections 810-996.6 (West, 1980).
46. Cal. Gov. Code Section 815 (West, 1980). Public entities include the State, the Regents of the University of California, counties, cities, districts, public authorities, public agencies, and any other political subdivisions or public corporations in the State. Cal. Gov. Code Section 811.2 (West, 1980). A sanitary district is a public entity. Ambrosini v. Alisal Sanitary District, 154 Cal. App.2d 720 (1957).
47. Cal. Gov. Code Section 814 (West, 1980). This section also provides that nothing in the code affects liability for other than money damages. Suits for injunctive or declaratory relief may always be brought.
48. Cal. Gov. Code Section 814.2 (West, 1980).
49. See Brown and Weinstock, Legal Issues, supra, note 30, at 290-291.
50. Cal. Gov. Code Section 815.6 (West, 1980).
51. Morris v. County of Marin, 18 Cal. 3d 901, 559 P.2d 606, 136 Cal. Rptr. 251 (1977) (county liable for failing to ascertain before issuing building permit that contractors carried adequate workers' compensation insurance. Such insurance was a prerequisite to a building permit. The county had no discretion to waive it.) The key is whether the regulatory body has discretion to allow the activity to proceed whether or not the statutory standard is met.
52. Cal. Gov. Code Sections 818.6, 821.4 (West, 1980). This does not apply to the entity's own property.

53. Cal. Gov. Code Section 815.2 (West, 1980).
54. Cal. Gov. Code Section 820 (West, 1980).
55. Johnson v. California, 69 Cal.2d 782, 447 P.2d 352, 73 Cal. Rptr. 240 (1968).
56. Cal. Gov. Code Section 830.5 (West, 1980).
57. Cal. Gov. Code Section 945.4 (West, 1980).
58. Cal. Gov. Code Sections 910-913.2 (West, 1980). The accrual of the claim is governed by the same factors as the accrual of claims against private parties. Cal. Gov. Code Section 901 (West Supp., 1984). This may lead to considerable extension of time, since personal injury or property damage claims do not accrue until with reasonable diligence they should have been discovered. In the DES suit, this was twenty and more years. In addition, if the claim for property or crop damage is based upon contract, the longer contract period will apply, rather than the injury period. Voth v. Wasco Public Utility District, supra, 56 Cal. App. 353, note 40.
59. Cal. Civ. Code Section 1668: Contracts contrary to policy of law (West, 1973).
60. Lease agreement of the City of Lodi, 1976; lease agreement between Lake Arrowhead Sanitation District and Hesperia Enterprises, Inc., 1977; Agreement for Allocation of Costs and Use of Reclaimed Water between Carmel Valley County Sanitation District and Carmel Valley Ranch, 1981.
61. Erickson v. Sears, Roebuck & Co., 240 Cal. App.2d 793, 59 Cal. Rptr. 143 (1966) (stepladder sold with instructions not to use on soft surfaces); Garcia v. Joseph Vince Co., 84 Cal. App.3d 868, 148 Cal. Rptr. 843 (1978) (fencing mask sold for use with blunt foils). The rationale of this defense is that it is the unforeseeable action of the user, not a defect in the quality of the product, that is the cause of the injury.
62. Cal. Gov. Code Section 815.6 (West, 1980). See discussion under governmental immunity.
63. Smith v. Dhy-Dynamic Co., 31 Cal. App. 3d 852, 107 Cal. Rptr. 907 (1973).

64. A prudent irrigator would probably object to an assumption clause completely exculpating the facility from any responsibility for not meeting the agreed non-statutory quality standards. The contract used by the City of Petaluma in 1981 suggests an equitable division of the risk. In this contract, the facility agrees to notify the buyer if the water fails to meet specified chemical standards. The buyer assumes the risk only of that damage occurring after notification.

65. Cal. Com. Code Section 2316 (West, 1964).

66. Cal. Com. Code Section 2719 (West Supp., 1984).

67. The following disclaimer was held sufficient to exclude warranty of fitness, but not warranty of merchantability: "Seller makes no warranty of any kind, express or implied, concerning the use of this product. Buyer assumes all risk in use or handling, whether in accordance with directions or not". Burr v. Sherwin Williams Co., 42 Cal 2d 682, 628 P.2d 1041 (1954).

68. The code also permits disclaimer of all implied warranties by sale "as is" or "with all faults." Cal. Com. Code Section 2316 (3)(a). This is clearly inapplicable to the sale of treated wastewater. However, if in the course of dealing or trade, certain risks are customarily assumed by the buyer, this custom will prevent contrary warranties from being implied. Cal. Com. Code Section 2316 (3)(a). Therefore, if common knowledge and custom place some risks upon the irrigator, it is possible that the supplier will not be held liable for injury resulting from these risks under an implied warranty. It is far safer to express all limitations upon warranties.

69. Dorman v. International Harvester Co., 46 Cal. App.3d 11, 120 Cal. Rptr. 516 (1975) (Disclaimer was ineffective to bar suit on implied warranty of fitness because not sufficiently conspicuous, although it was placed close to where the buyer signed and was in slightly larger type.) The Commercial Code does not require that a disclaimer of express warranties be set out from the body of the contract. It does require notice to the buyer. Because the scope of implied warranties in the sale of treated wastewater is untested, and because these sale contracts are likely to be

construed to the disadvantage of the seller (see following text discussion), it would be wise to ignore this subtle distinction between disclaimers of express and implied warranties and print any disclaimer in bold-face type.

70. Hauter v. Zogarts, supra, 14 Cal. 3d 104, note 42; Dorman v. International Harvester Co., supra, 46 Cal. App. 3d 11, note 69.

71. Cal. Civ. Code Section 1668 (West, 1973): Contracts contrary to policy of law: "All contracts which have for their object, directly or indirectly, to exempt anyone from responsibility for...violation of law, whether willful or negligent, are against the policy of the law." The sixth circuit federal court of appeals, applying California law, held that Section 1668 prohibited disclaimer of an express warranty of seed germination found to arise under the certification standards of the California Seed Law. Agricultural Service Ass'n, Inc. v. Ferry-Morse Seed Co., 551 F.2d 1057 (6th Cir. 1977). See Callahan, The Effect of Warranties on Seed Sales, 11 U.C.D. L. Rev. 335 (1978).

72. Cal. Com. Code Section 2719 (West Supp., 1984): Contractual Modification or Limitation of Remedy. The statute allows the seller to limit remedies sought on a breach of warranty theory. The buyer may still sue on a strict liability or negligence theory. There is a possibility that a remedy limitation clause might also cover negligent breach of warranty, even negligent breach of a warranty imposed by law. Sellers have traditionally not been allowed to disclaim liability for negligence, but in a few decisions involving sophisticated commercial parties, such disclaimers have been upheld. See Delta Airlines Inc. v. Douglas Aircraft Co., 238 Cal. App.2d 95, 47 Cal. Rptr. 518 (1965); Southern Cal. Edison Co. v. Harnischfeger Corp., 120 Cal. App.3d 842, 175 Cal. Rptr. 67 (1981). Although Cal. Civ. Code Section 1668 would prohibit negligence disclaimers involving water quality warranties imposed by law, it is possible that remedy limitation clauses covering negligent breach of these warranties would be upheld, at least in commercial contracts. It

is therefore advisable for the remedy limitation clause to state that it applies to negligent as well as non-negligent breach of warranty.

73. Lemat Corp. v. American Basketball Ass'n., 51 Cal. App. 3d 267, 124 Cal. Rptr. 388 (1975), held that Cal. Civ. Code Section 1668 does not bar shifting the responsibility to pay damages by indemnification because this does not exempt a party from primary liability. The same reasoning would support limitation of remedy, as long as the limitation does not amount in practical effect to an exemption.

74. Cal. Com. Code Section 2719 (West Supp., 1984), Uniform Commercial Code Comment 1.

75. It would seem that the substantial value requirement could be satisfied by limiting damages to the price of the wastewater contract, or possibly even less. In the sale of crop seeds, a commercial activity analogous to the sale of wastewater for agricultural irrigation, the courts have upheld warranty limitations allowing only the return of the cost of the seed, despite damages amounting to the loss of a crop. For another view, see Callahan, The Effect of Warranties on Seed Sales, supra, note 71, in which the author argues against the evidence that under Cal. Com. Code Section 2719 the outcome should be different.

76. Cal. Com. Code Section 2725 (West Supp., 1984).

77. Unlike tort actions, warranty actions accrue at the date of breach, not the date of discovery. Inobviousness of damage would not allow the claimant to extend the statute of limitations in an action under the commercial code. Cal. Com. Code Section 2725 (2) (West Supp., 1984).

78. Seely v. White Motor Co., supra, 63 Cal. 2d 9, note 36, at 17. The seller is always potentially liable to injured third parties under design defect and express warranty theories because the risk assumption and warranty limitation clauses only restrict claims that may be brought by the buyer. In addition, third parties may bring a suit based on negligent treatment or negligent entrustment by the seller.

79. American Motorcycle Association v. Superior Court, 20 Cal.3d 578, 578 P.2d 899, 146 Cal. Rptr. 182 (1978); Rossmoor Sanitation, Inc. v. Pylon, Inc, 13 Cal.3d 622, 532 P.2d 97, 119 Cal. Rptr. 449 (1975).

80. see note 73.

81. S.C.M. Corp. v. U.S. Slicing Machine Co., 73 Cal. App.3d 49, 140 Cal. Rptr. 559 (1977); Rossmoor Sanitation, Inc. v. Pylon, Inc., supra, 13 Cal. 3d 622, note 79. If an indemnity clause does not expressly cover negligence by the indemnified party, it is a "general clause" and will not be enforced if the indemnified party has been more than passively negligent. Passive negligence is mere non-action, such as failure to discover a dangerous condition created by others; active negligence is action creating a dangerous condition. The agreement found in Appendix C of *Evaluation Of Agricultural Irrigation Projects Using Reclaimed Water* (Office of Water Recycling, California State Water Resources Control Board, 1981) contains such a general indemnification clause: "_____ assumes all liability for damage" and "agrees to hold harmless the District...." This would provide for indemnification against passive negligence. Similar provisions purporting to hold a party harmless "in any suit at law," "from all claims for damages," and "from any cause whatsoever" have been ineffective when the party promising to indemnify has proven active negligence by the other party. The disadvantage to a general clause is that it invites litigation by the indemnifying party's insurer over the issue of active negligence.

82. Williams v. Walker-Thomas Furniture Co., 350 F.2d 445 (D.C. Cir. 1965).

83. See Dorman v. International Harvester Co., supra, 46 Cal. App. 3d 11, note 69; Tunkl v. Regents of Univ. of Cal., 60 Cal. 2d 92, 383 P.2d 441, 32 Cal. Rptr. 33 (1963).

84. Beynon v. Gardon Grove Medical Group, 100 Cal. App.3d 702, 161 Cal. Rptr. 146 (1980); Weaver v. American Oil Co., 276 N.E.2d 144 (1971).

85. Benson, Barbara. Agricultural Irrigation with Treated Wastewater in California: Contractual Allocation of Public Health Risks (1982) (not published at date; manuscript on file at U.C. Davis Law Review Office).

86. See for example the lease agreements used by the City of Lodi. Most contracts reviewed did not address the issue of liability. One attempted to shift all responsibility to the buyer/lessee by broadly worded indemnification. If a third-party claim were brought, it is likely that the buyer/lessee's insurer would contest responsibility under an over-broad and unspecific indemnification clause.

CHAPTER 12

FATE OF WASTEWATER CONSTITUENTS IN SOIL AND GROUNDWATER: NITROGEN AND PHOSPHORUS

F. E. Broadbent and H. M. Reisenauer

NITROGEN

Introduction

In wastewater irrigation, the primary concern with respect to nitrogen is the possibility of nitrate contamination of domestic water supplies and the attendant risk of methemoglobinemia in human infants. Although the incidence of methemoglobinemia, or "blue baby disease," in the United States is very low, the Public Health Service has set 10 mg/L nitrate-N as the level that should not be exceeded in drinking water. The risk is based on the possibility of reduction of nitrate to nitrite in the digestive tract of infants below the age of 6 months. Nitrite absorbed into the blood stream can combine with hemoglobin, thereby reducing its capacity to carry oxygen. Older humans are much less susceptible to the disease than are very young infants. Methemoglobinemia is much more common in ruminant animals than in humans, but its occurrence is usually associated with high nitrate concentrations in forage rather than in drinking water.

Aside from the possible risk of groundwater contamination, it is desirable to recycle nitrogen wherever feasible, since it is an essential nutrient required for the production of food and fiber. Its reuse also represents energy conservation.

Forms of N in Wastewaters

Wastewaters typically contain three forms of nitrogen: organic, ammonium, and nitrate; low concentrations of nitrite may also be present. The relative proportions of these various forms varies with the origin and treatment history of the wastewater, but most commonly ammonium (NH_4^+) is the principal form, usually falling in the concentration range of 5 to 40 mg N/L. The organic fraction, which may be either soluble or fine particulates, consists of a complex mixture including amino acids, amino sugars, and proteins. All of these are readily convertible to ammonium through the action of microorganisms in the wastewater or in the soil (where they are even more readily convertible) to which the wastewater is applied. Except in the case of food-processing wastewater, the organic component represents less than half the total N present. Nitrate concentrations may range from 0 to more than 30 mg N/L. Where aerobic treatment processes have occurred, some of the ammonium in the treated water often will have been converted to nitrate through the action of nitrifying bacteria.

N Retention in Soil

Some ammonia may be volatilized from wastewaters with pH values above 7.0. Certain types of clay minerals that commonly occur in California soils, particularly in soils subject to considerable shrinking and swelling during wetting and drying cycles, have the ability to trap ammonium ions within the crystal lattice. Ammonium ions thus fixed are not displaced readily by other cations in the soil solution, such as calcium, magnesium, or sodium, nor are they accessible to nitrifying bacteria. A fraction of any application of ammonic N may be fixed in this way, but over the long term it would not have an important effect on the nitrogen budget.

Like other cations in wastewater, ammonium ions can be adsorbed by the negatively charged clay and organic colloids in soil. Unlike the fixed form, adsorbed ammonium can be readily exchanged by other ions in the soil solution. In all except very sandy soils, the ammonium adsorption capacity of soils is sufficient to retain all ammonium from a single slow-rate application near the surface of the soil. For example, if a fairly high ammonium-N concentration of 50 mg/L is assumed in a wastewater applied at the rate of 3 inches (7.5 cm) to a soil with the fairly low exchange capacity of 10 meq/100 g, only 3.8% of the exchange capacity in the surface 2 inches (5 cm) of soil would be required to retain it. Cumulative buildup of adsorbed ammonium is unlikely to occur. The retention of ammonium ion is always temporary, lasting only a few days or weeks, since the adsorbed ammonium is readily oxidized to nitrate by nitrifying bacteria, thereby being made mobile and capable of rapidly moving away from the adsorption site through mass flow or diffusion.

Application of volumes of water substantially higher than the usual 1-4 inches (2.5-10 cm) per week employed in slow-rate application can result in saturation of the ammonium retention capacity of the soil, in which case ammonium ion may leach to considerable depths in the soil profile.

A mechanism of temporary ammonium retention involves assimilation by soil microorganisms. Net immobilization by microorganisms occurs in the presence of decomposable organic residues of low N content. Where wastewater is applied to land following incorporation of mature crop residues, N immobilization may account for as much as 50 lb/acre (56 kg/ha), but values of 20-40 lb/acre (22-45 kg/ha) are more common. Net immobilization normally occurs only during the first 2-3 weeks of crop residue decomposition.

N Transformations in Soil

Three kinds of soil transformations of the N contained in wastewater are important. The first of these is mineralization:

$$\text{Organic N} \longrightarrow NH_4^+ \qquad [12\text{-}1]$$

This transformation involves a wide range of different microorganisms, both aerobic and anaerobic. As has been noted previously, the relatively low concentrations of organic N are quickly converted to ammonium after application to soil. The sequel to mineralization is nitrification:

$$NH_4^+ + 3/2\ O_2 \longrightarrow NO_2^- + H_2O + 2\ H^+ \qquad [12\text{-}2]$$

$$NO_2^- + \tfrac{1}{2}\ O_2 \longrightarrow NO_3^- \qquad [12\text{-}3]$$

The first reaction is carried out by bacteria of the genus *Nitrosomonas* and its relatives, and the second is carried out by *Nitrobacter* and related species. These bacteria are almost universally present in soils, although populations may be quite low in subsoils or dry sandy soils. Application of wastewaters containing ammonium to such soils will result in a buildup of nitrifying bacteria, although maximum numbers may not be attained for a few weeks. In soils where wastewater is applied regularly, nitrification is normally rapid unless temperatures are very low. Nitrification rates range from 5 to 70 lb N/acre·day (6 to 78 kg N/acre·day). Thus the ammonium in 3 inches of wastewater containing 50 mg NH_4-N/L, equivalent to 34 lb N/acre (38.1 kg N/acre), would be nitrified within a week at most.

Another important transformation of nitrogen in soils is denitrification. Although nitrate is the end-product of the normal series of nitrogen transformations in aerobic soils, it can undergo reduction to N_2O and N_2 if oxygen is limiting and if decomposable organic matter is present to furnish energy for the process. The microorganisms responsible for denitrification are facultative anaerobic bacteria, which normally use oxygen from the air for metabolism, but they can use nitrate as a terminal electron acceptor when concentrations of oxygen are very low. The sequence of products is:

$$NO_3^- \longrightarrow NO_2^- \longrightarrow N_2O \longrightarrow N_2 \qquad [12\text{-}4]$$

Both N_2O and N_2 are gases and may escape from the soil, but N_2 is usually the predominant form.

Denitrifying bacteria are common soil organisms of widespread distribution. Rates of denitrification are controlled primarily by the supply of available organic matter and secondarily by the aeration status of the soil, provided the concentration of nitrate available for reduction is not limiting. Theoretically, 1.3 units of decomposable carbon are required for each unit of nitrate-N denitrified, but somewhat more than this amount is necessary in natural systems, because many other heterotrophic microorganisms compete with denitrifying bacteria for organic substrates. Only in wastewater of high biochemical oxygen demand, such as cannery wastes, is there sufficient organic matter to exert a significant influence on the rate of denitrification. Organic matter in soils is often most abundant near the surface, and its availability is likely to be greater there than in the subsoil. This means that the zone of most active denitrification is apt to be close to the surface. For example, Rolston et al. [1] observed maximum rates of production of N_2O and N_2 within the top 10 cm of soil.

The requirement for oxygen deficiency in denitrification near the soil surface is explained by the observation that virtually all soils may experience temporary or spatially restricted anaerobism. Saturation may occur during irrigation or rainfall with the exclusion of oxygen from the soil pores, or oxygen deficiency may occur in an unsaturated soil in sites where the rate of oxygen consumption exceeds the rate of replenishment, particularly in the smaller pores. Some denitrification has been shown to occur in many soils considered to be well aerated. A layer of impeded drainage in a soil profile favors denitrification.

The quantity of N lost through denitrification may vary from none to more than 90% of that applied, depending on soil properties and water management. In general, coarse-textured, well-drained soils of low organic matter content have a low potential for denitrification loss. Sandy loam and loam soils have a medium denitrification potential, and fine-textured soils such as silt loams, clay loams, and clays have a high potential for denitrification. The presence of a layer of restricted drainage in the profile increases the chances for loss by denitrification. Lund and Wachtel [2] have rated a number of California soils according to their denitrification potential. For practical purposes, denitrification can be disregarded in soils of low potential; however, in soils of medium potential, losses in the 10-20% range can be expected, and in soils of high potential, losses of 20-40% can be expected. Denitrification losses are correlated with frequency of irrigation; hence, better N utilization efficiency (less denitrification) can be obtained with fewer irrigations.

Ammonia Volatilization

Where wastewater is applied by sprinkler irrigation, and to a lesser extent by surface irrigation, some loss of N as ammonia is probable, since wastewaters are typically alkaline in reaction. Henderson et al. [3] suggested that volatilization losses during sprinkler irrigation of water with a pH of 7.5-8.5 would amount to less than 20% of the total applied. The possibility of adsorption of gaseous ammonia on leaf surfaces or soil may further reduce this loss.

Plant Uptake of Applied N

The fate of N in applied wastewater depends heavily on the proportion of nitrate in the downward-moving soil solution, which is intercepted and absorbed by plant roots. For example, Kardos and

Sopper [4] reported that application of sewage effluent to forest and cropland at the rate of 1 inch/week over a period of 6 years did not increase the nitrate-N concentration of soil solution samples above the 10 mg/L Public Health Service standard, but this limit was exceeded when the application rate was 2 inches/week.

A crop does not utilize all of the inorganic N present in the root zone. The fraction of the total amount assimilated depends on the plant, depth and distribution of roots, stage of growth, rate of water movement through the root zone, and other factors. In general, the efficiency of uptake of applied N is seldom much in excess of 50% and is often less. Table 12-1 lists values for N uptake efficiency for a few important crops in California in conventional fertilizer practice, but these values may be somewhat higher than would be obtained with a diffuse and dilute source of N such as wastewater.

Table 12-1. Nitrogen utilization efficiency for some crops in California.

Crop	N application rate (kg/ha)	Uptake of applied N (%)
Corn	180	56
Sugarbeet	135	47
Tomato	112	64
Potato	270	39
Rice	90	34

Another consideration is that a certain minimum concentration of nitrate in the soil solution is required to meet the needs of crops. Broadbent and Rauschkolb [5] reported 10-13 mg/L NO_3-N in the soil solution below the root zone of unfertilized corn plants suffering from nitrogen deficiency. Grasses, especially perennials, tend to be more efficient in N uptake than are row crops. For most crops, part of the plant N will be recycled to the soil and eventually be made available to a subsequent crop. In some instances, accumulation of roots and other crop residues may result in long-term storage of significant amounts of nitrogen in the soil profile as these residues are converted into stable soil humus: for example, long-term application of wastewater to a previously uncropped area near Bakersfield [6] nearly tripled the organic N in the soil profile. However, in most situations, the application of wastewater to crops will not materially alter the organic N level of the soil because of its low content of organic carbon.

From the standpoint of long-term application of wastewater, N input levels should be adjusted to compensate for N removal by the harvested portion of the crop plus expected losses from the system by volatilization and leaching. Total plant uptake of N may greatly exceed crop N removal, particularly in fruit crops. Table 12-2, adapted from Rauschkolb et al. [7] and *Better Crops with Plant Food* [20], gives representative crop yields and crop removals of N and P per ton of yield of the harvested component of a number of crops.

Leaching Losses

Nitrate in wastewater applied to land is subject to leaching if not intercepted by plant roots, immobilized by microorganisms, or denitrified. Leached nitrate may be transported to surface waters by tile drains (if these are present) or by seepage on sloping terrain. Otherwise it will move through the profile into groundwater. The magnitude of leaching losses is dependent on quantity of water applied, evapotranspiration, nature of the crop grown, and soil profile characteristics. The total quantity of N leached is much more significant in terms of pollution hazard than is the nitrate concentration, although most attention is usually given to the 10 mg/L public health concentration standard for drinking water. A small volume of water leached, even though high in nitrate concentration, is of less concern than a large volume of leachate at lower nitrate content, since the latter represents a much greater mass emission of nitrate.

Table 12-2. Crop uptake of N and P in relation to yield of some selected crops.[a]

Crop	Component	Representative yield (ton/acre)	N removal	P removal
			(lb/ton of yield)	
Field crops				
Alfalfa	hay	5.8	65	5.3
Barley	grain	2.0	42	7.2
	straw	2.5	17	2.8
Beans, dry	beans	1.34	78	-
Corn	grain	4.5	33	6.8
	silage	25.0	9	-
	stover	2.0	21	2.3
Cotton	seed	0.85	79	22.4
	stalks	0.63	115	16.0
Oats	grain	1.34	42	-
Rice	grain	3.3	31	-
	straw	3.5	10	-
Safflower	grain	1.34	69	-
Sorghum	grain	2.0	42	6.6
	stover	1.8	21	3.4
Soybeans	grain	1.25	134	12.0
	stover	1.25	46	4.0
Sugarbeets	beets	30.0	4	0.2
	tops	30.0	4	0.4
Wheat	grain	2.0	39	8.0
	straw	3.5	18	2.0
Mixed grass	hay	2.0	47	-
Irrigated pasture		2.0	34	-
Fruits and nuts				
Apricot	fruit	8.0	4	-
Cherry	fruit	4.0	5	-
Grapes	fruit	10.0	2	-
Peach	fruit	16.0	3	-
Pear	fruit	15.0	2	-
Plum	fruit	8.0	7	-
Prune	fruit	8.0	7	-
Almond	nuts	0.9	67	-
Walnut	nuts	1.0	53	-
Grapefruit	fruit	11.0	4	-
Orange	fruit	8.0	5	-
Lemon	fruit	13.0	4	-
Avocado	fruit	2.6	8	-
Olive	fruit	2.1	4	-
Strawberry	fruit	19.0	4	-

Table 12-2 continued.

Crop	Component	Representative yield (ton/acre)	N removal	P removal
			(lb/ton of yield)	
Vegetables				
Broccoli	heads	5.0	13	-
Carrots	roots	19.0	4	-
Potato	tubers	20.0	8	-
Tomato	fruits	25.0	4	0.3
	vines	30.0	3	0.4
Turfgrasses				
Bent		2.2	69	-
Bermudagrass		4.0	63	-
Kentucky bluegrass		2.2	62	-
Fuel crops				
Pulpwood (slash pine)	wood	40 cords	150 lbs/acre	13 lbs/acre
	bark & branches		190 lbs/acre	4 lbs/acre

[a] Adapted from Rauschkolb et al. [7] and from Better Crops with Plant Food [20].

Letey et al. [8] measured effluent volumes and nitrate concentrations of tile-drainage waters from commercial farms in the Imperial, Coachella, Ventura-Oxnard, San Joaquin, and Salinas valleys of California. They found that nitrate concentrations in effluents were not well correlated with N application rate, effluent volume, or soil profile characteristics. However, the amount of N leached through tile drains was quite well correlated with total water discharge and total N applied. Total mass emissions of nitrate over a given period of time could not be estimated from the nitrate concentrations of the tile effluents. They found emissions to be very low where alfalfa was grown, indicating high efficiency of plant uptake of the applied N.

There is considerable evidence that nitrate is accumulating in groundwater in California, as for example in the study by Nightingale [9]. However, the contribution of surface-applied N to these accumulations is not well defined. Both nitrate concentrations and water movement in soils are subject to a widely ranging spatial variability; consequently, calculations of mass flow of nitrate through the soil are subject to considerable uncertainty. Rible et al. [10] estimated nitrate leaching past the root zone at 83 locations in central and southern California from the equation:

$$N_d = \frac{(NO_3\text{-}N) x D}{10} \qquad [12\text{-}5]$$

where N_d is N drained past the root zone in kg/ha·year, NO_3-N is in mg/L, and D is drainage volume in cm/year.

The value of D was calculated from the product of the volume of water applied and the leaching fraction. Considering data from selected sites where records of water and N inputs were most reliable, they found that mass emissions of N were positively correlated with both N applications and drainage volume, whereas nitrate concentrations were not correlated with either of these factors.

Soil profile characteristics were found to be of major importance in influencing the amount of nitrate moving past the root zone. Lund et al. [11] reported significant correlations between soil nitrate concentrations below the root zone and clay content of the upper soil profile. Soils that have high water infiltration rates tend to be relatively low in organic matter and do not readily develop the anoxic conditions that are conducive to denitrification. Such soils are usually sandy and may have no layers in the profile that restrict water movement. High leaching of nitrate is probable under these conditions, particularly where N applied exceeds crop uptake to any significant degree. On the other hand, clayey soils or soils with clay layers or textural discontinuities in the profile typically have slow water movement and are much more likely to develop the anaerobic conditions that favor N loss through denitrification. Consequently, nitrate usually is leached less from a fine-textured soil than from a coarse-textured one with equal N input. Moreover, the fraction of applied N leached increases with increasing level of N input. This is illustrated by measurements of mass emissions of N from columns of Panoche sandy loam receiving 3 inches (7.6 cm) of wastewater per week over several months. Where the applied water contained 61 mg N/L of NH_4^+-N, the effluent contained nitrate equivalent to 83% of the input N. When the applied wastewater contained 21 mg N/L, only 16% was leached as nitrate [12].

Estimates of the quantity of N leached in a given situation can be made by subtracting N utilized by the crop from the total N applied and then using a reasonable estimate of denitrification loss to adjust the remainder. A guide to the magnitude of these estimates is provided by the soil textural class as noted in the section on nitrogen transformations in soil.

PHOSPHORUS

The use of treated municipal wastewater for irrigating commercial crops is both practical and safe, provided the capacity of the soil-crop system to retain the applied nutrients is not exceeded. Assuming a P content of 10 mg/L, a season's irrigation (3 feet or 0.9 m of water) supplies 81 lb/acre of P (90.7 kg/ha), equivalent to 186 lb/acre (208 kg/ha) of P_2O_5. Although this is not an exceptionally high application rate, it is considerably above the average fertilizer application for the state (Table 12-3), and if applied over several years to a crop with a low P-removing rate (Table 12-2) on a soil of minimal phosphate sorption capacity, ground- or surface-water contamination can result [13, 14].

Table 12-3. Common rates of fertilization in California.[a]

Crop category or crop	Common rate (lb/acre) and (percentage of acreage treated)		
	N	P_2O_5	K_2O
Citrus and subtropical	137 (92)	110 (16)	78 (16)
Field crops	124 (84)	58 (30)	116 (4)
Fruits and nuts	141 (80)	78 (7)	253 (9)
Pasture (not range)	62 (12)	35 (11)	14 (<1)
Turf	523 (92)	124 (73)	247 (77)
Vegetables	167 (96)	86 (82)	60 (57)
Grapes	54 (79)	27 (11)	126 (10)

[a] Adapted from Rauschkolb and Mikkelsen [19].

Phosphates added to soil may be taken up by the crop, accumulated by the solid phase of the soil in sorption and precipitation reactions, or lost from the system in percolating and runoff waters or by erosion. Reactions with the soil and crop removal account for the largest fraction of the added P. Only small amounts--less than 3% of that added annually--have been found in drainage waters. Studies of the reactions of phosphates in agricultural soils have revealed the important roles of the hydrous oxides iron and aluminum, and of calcium. Quantitatively the data are conveniently represented in the form of sorption isotherms, in which the amount of P sorbed under a specific set of conditions is expressed as a function of the concentration of phosphate in the aqueous phase. The simplest of these is the Freundlich isotherm:

$$P_r = kc^{1/n} \qquad [12\text{-}6]$$

where P_r is the amount of P retained at aqueous phase phosphate concentration c, and k and n are empirical constants. Phosphorus retention, however, does not reach equilibrium, as the equation implies, but involves an initially fast reaction followed by a slow transition to a less soluble product. Likewise, the reverse of the retention reaction--the dissolution of retained phosphate--is rapid following the addition of a soluble phosphate; it then slows with time [15].

In spite of the great differences between soils and their capacities to retain P, the nature of retention reactions is remarkably uniform [16], and their extent can be estimated from relatively simple relationships. Ryden and Pratt [17] have utilized this characteristic in developing a model for predicting the useful life of a field filtering system. The capacity of the system to retain phosphate is determined from measurement of the P sorption capacity of the soil, the amount of P supplied in the wastewater, and the amount removed in the harvested crop. Evaluations of the model [18] have indicated that it satisfactorily predicts the capacity of soils to retain phosphate and thus allows estimation of the maximum useful life of acid-soil systems. It does not provide estimates of phosphate additions to deep percolating and drainage waters from desorption reactions and from preferential transport of soil solution through macropores. A recent review of data from field sites where wastewater irrigation has been practiced for an extended period (21) indicated only infrequent incidences of significant P penetrations into subsoil layers. Because of the many uncertainties involved and the lack of a single standard for acceptable ground-water phosphate levels, sites should be monitored frequently, particularly as P additions approach the estimated capacity.

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CHAPTER 13

FATE OF WASTEWATER CONSTITUENTS IN SOIL AND GROUNDWATER: TRACE ELEMENTS

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INTRODUCTION

The term trace element is used to denote a group of otherwise unrelated chemical elements present in the natural environment in low concentrations. In small quantities, many elements (e.g, F, Si, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Se, Mo, Sn, I, Cl, B) are essential to biological growth. At a slightly higher concentration, many elements may become toxic to plants and/or animals. There are also elements (e.g., As, Cd, Pb, Hg) that have no known physiological function and are always considered biologically harmful.

In the soil, uncontrolled trace-element inputs are undesirable, because once accumulated in the soil, these substances are in most cases practically impossible to remove and subsequently may lead to (1) toxicity to plants grown on the affected soils, (2) absorption by crops, resulting in trace-element levels in the plant tissue considered harmful to the health of humans or animals who consume the crops, and (3) transport from soils to underground or surface water, thereby rendering the water unfit for its intended use.

Wastewaters always contain trace elements. Here we review the fate of trace elements applied to soil during wastewater irrigation. Our analysis is based upon the quantity of irrigation water that would commonly be applied to irrigate crops in arid and semi-arid regions, which is 4 ft/year (1.2 m/year).

TRACE ELEMENTS IN WASTEWATER

The occurrence of trace elements in the wastewater is related to the source water and activities in the urban environment. Trace elements are widely used in industrial processing and in manufacturing consumer goods [1]. Even when they are not used, trace elements may occur as contaminants in many products used in manufacturing. The deterioration of storage and transmission equipment in the community water supply system and the wear of household plumbing fixtures also contribute to their presence in the water. For these reasons, small amounts of trace elements are always found in domestic wastewater [2]. Many publicly owned treatment works (POTWS) also receive industrial waste discharge, and a consistently high concentration of trace elements usually is an indication of industrial waste inputs. The actual concentration of trace elements in the wastewater, however, may vary considerably with time within a particular treatment plant as well as among treatment plants in various communities [3,4]. Experimental data also demonstrate that most trace elements in the wastewater (except boron) are adsorbed onto the organic or inorganic solids or form sparingly soluble inorganic precipitates.

Although a conventional wastewater treatment system is not designed to remove the trace elements because they are adsorbed on or precipitated by suspended solids, they are effectively removed from the wastewater by removal of suspended solids. Under the normal operating conditions, trace-element concentrations of primary effluents are reduced by 70% to 90% through secondary treatment [5]. Typical concentration ranges for trace elements in wastewater effluents are summarized in Table 13-1. A comparison of the median concentrations for trace elements in wastewater effluents listed in Table 13-1 with the irrigation water-quality criteria established by U.S. Environmental Protection Agency in 1973 [6] shows that the trace-element concentration (except boron) in at least half of the POTWS surveyed will meet the trace-element requirements of irrigation water. Since the trace-element threshold limits of the irrigation-water-quality criteria were intended to protect even the most sensitive plants from harmful effects, wastewaters from the other half of the POTWS may be suitable for irrigation if their use is carefully planned and managed.

EFFECTS OF TRACE ELEMENTS ON PLANT GROWTH

Among the trace elements commonly found in the wastewater, B, Cd, Cu, Mo, Ni, and Zn are considered to present a potentially serious hazard if they are introduced into the cropland soils in an uncontrolled manner [7]. The potential hazards associated with other trace elements in the soil are ruled out by their attenuated chemical

Table 13-1. Concentrations of trace elements in wastewater from municipal treatment plants (mg/L).[a]

Element	Primary effluent		Secondary effluent		Water-quality criteria for irrigation[b]	
	Range	Median	Range	Median	Long term	Short term
As	<0.005 -0.03	<0.005	<0.005 -0.023	<0.005	0.10	10
B	<0.01 -2.5	1.0	<0.1 -2.5	0.7	0.75	2
Cd	<0.02 -6.4	<0.02	<0.005 -0.15	<0.005	0.01	0.05
Cr	<0.05 -6.8	<0.05	<0.005 -1.2	0.02	0.10	20.0
Cu	<0.02 -5.9	0.10	<0.006 -1.3	0.04	0.20	5.0
Hg	<0.0001-0.125	0.0009	<0.0002-0.001	0.0005	--	--
Mo	<0.001 -0.02	0.008	0.001 -0.018	0.007	0.01	0.05
Ni	<0.1 -1.5	0.1	0.003 -0.6	0.004	0.2	2.0
Pb	<0.2 -6.0	<0.2	0.003 -0.35	0.008	5.0	20.0
Se	<0.005 -0.02	<0.005	<0.005 -0.02	<0.005	0.02	0.05
Zn	<0.02 -2.0	0.12	0.004 -1.2	0.04	2.0	10.0

a. Based upon information presented by Bouwer and Chaney [24] and accumulated by the authors from a number of sources.

b. From U.S. Environmental Protection Agency [6].

activities in the soil or by their infrequent occurrence and exceptionally low concentration in the wastewater. Following the common crop production practice, Mn, Fe, Al, Cr, As, Se, Sb, Pb, and Hg inputs through application of treated wastewater to land should not result in phytotoxicity or expose consumers to potentially hazardous trace-element levels. Concentrations of selected trace elements normally found in the soil and plant tissue and their effects on crop growth are summarized in Table 13-2. At these reported levels, trace elements do not appear to cause any serious concern.

Among those elements that may limit the use of wastewater for irrigation, Cd, Cu, Ni, and Zn are singled out for their potential phytotoxic effects. Assuming that a wastewater with typical trace-element concentration is applied at 4 ft/year (1.2 m/year), the annual inputs of Cu, Ni, and Zn will be 1.2, 0.24, and 1.8 kg/ha, respectively. For Cu and Zn, these input levels are far below the amounts routinely used to correct trace-element deficiencies in the soil. Even if the concentrations of Cu and Zn in the wastewater are one order of magnitude higher, their inputs to the soil are still in line with the recommended fertilization practice. It is unlikely that short-term use of wastewater for crop irrigation could result in crop injuries due to Cu, Ni, or Zn. Since these elements may accumulate in the soil, the long-term toxic effects require further examination.

To safeguard plants from possible detrimental effects of sludge-borne trace-elements in cropland sludge applications, the U.S. Environmental Protection Agency has recommended that the cumulative total loading of Cd, Cu, Ni, Zn, and Pb during the land application of sludges be limited according to the cation exchange capacity (CEC) of the receiving soil [8,9]. In the absence of any trace-element input criteria--specifically for wastewater irrigation--the EPA-suggested limits for trace elements through sludge application to agricultural land can be used as a point of reference. Given trace-element concentrations in wastewater for sludge loading criteria and annual water application rate, one may calculate the time required for a soil to reach the loading limits of metals in the water (Table 13-3).

Table 13-2. Concentrations of selected trace elements normally found in soil and plant tissue (μg/g) and their impact on plant growth.

Element	Soil concentration[a] Range	Soil concentration[a] Typical	Typical concentration in plant tissue Range	Impact on plant growth[b]
As	0.1 -40	6	0.1 -5	Not required
B	2 -200	10	5 -30	Required, wide species differences
Be	1 -40	6	--	Not required: toxic
Bi	--	--	--	Not required: toxic
Cd	0.01-7	0.06	0.2 -0.8	Not required: toxic
Cr	5 -3000	100	0.2 -1.0	Not required: low toxicity
Co	1 -40	8	0.05-015	Required by legume at <0.2 ppm
Cu	2 -100	20	2 -15	Required at 2-4 ppm: toxic at >20 ppm
Pb	2 -200	10	0.1 -10	Not required: low toxicity
Mn	100 -400	850	15 -100	Required: toxicity depends on Fe/Mn ratio
Mo	0.2 -5	2	1 -100	Required at <0.1 ppm: low toxicity
Ni	10 -1000	40	1 -10	Not required: toxic at >50 ppm
Se	0.1 -2.0	0.5	0.02-2.0	Not required: toxic at >50 ppm
V	20 -500	100	0.1 -10	Required by some algae: toxic at >10 ppm
Zn	10 -300	50	15 -200	Required: toxic at >200 ppm

a. Derived from data published by Bowen [25], Allaway [12], Lisk [26], Page [27] and Chapman [28].

b. Concentration listed for plant tissue are on a dry-weight (70 C) basis.

Table 13-3. Calculated length of time for wastewater-irrigated agricultural soils to reach heavy-metal loading limits.

Element	Typical concentration (mg/L)	Annual input (@1.2 m/yr water depth)	Suggested loading (kg/ha) at soil CEC[a]			Time (in yrs) to reach soil loading limit at CEC[a]		
			<5	5-15	>15	<5	5-15	>15
Cd	0.005	0.06	5	10	20	82	167	333
Cu	0.10	1.2	125	250	500	104	208	416
Ni	0.02	0.24	125	250	500	521	1042	2083
Zn	0.15	1.8	250	500	1000	139	278	556
Pb	0.05	0.60	500	1000	2000	833	1667	3333

a. Cation exchange capacity expressed in units of meq/100g soil.

When a wastewater with typical trace-element concentrations is applied at 4 ft/year (1.2 m/yr) the time required for a trace-element to reach its limit in the soil varies from 82 years (for Cd on soil with CEC less than 5 meq/100 g) to more than 3000 years (for Pb on soil with CEC greater than 15 meq/100 g). Since the limits of metal input are specified for soils of pH > 6.5, the pH of the metal-affected soils to which the metals are applied must be maintained above 6.5.

Unlike Cu, Ni, and Zn, cadmium is not an essential element for crop growth. In the soil, the problems associated with the additions of Cd are twofold. Cadmium is usually phytotoxic at low concentrations, yet even before any phytotoxic symptom is detected, the Cd added to the soil may drastically elevate the Cd level in the affected plant tissue. However, the tolerance of plant species to levels of Cd added to the soil is highly variable; Table 13-4 summarizes the tolerance of selected crop species to Cd in the soil. The annual input limit (<0.5 kg/ha) suggested by the U.S. Environmental Protection Agency for cropland receiving sludge was intended to protect against the possibility of accelerated entry of Cd into the human food chain. At the irrigation rate of 1.2 m/year, the concentration of Cd in the applied wastewater could reach 0.04 mg/L before this limit is exceeded. It is conceivable that the annual Cd input may become a factor limiting the application of some wastewaters to land.

The role of B in the land application of wastewater is somewhat unusual. In wastewater, boron probably occurs in the form of undissociated boric acid. It is not removed very effectively during wastewater treatment. Being uncharged, B also passes through soils much more rapidly than the other trace elements. Although B is essential for crop growth, the margin between levels considered essential to plant growth and those considered phytotoxic is extremely narrow. Plants grown on soils whose water-extractable boron (soil saturation extract) is less than 0.04 mg/L often exhibit symptoms of B deficiencies, whereas at concentrations in excess of 1.0 mg/L, B is toxic to many boron-sensitive crop species [10]. Unlike other elements (e.g., Cd, Cu, Ni, Zn, Pb, Cr, Fe, Mn, Se, Mo, As, Hg, Sb and Al) that tend to deposit near the ground surface following the application, B is only weakly adsorbed and may rapidly pass through

Table 13-4. Relative tolerance of plant species to various levels of cadmium added to soil.[a]

Range of soil-Cd addition (μg/g)	Plant species showing 50% yield reduction
10-50	Spinach (*Spinacia oleracca* L.), soybean (*Glycine max* Meer.), curlycress (*Lepidium sativa* L.), sweet corn (*Zea mays* L.), upland rice (*Oryza sativa* L.)
50-100	Sudangrass (*Sorghum halepense* Perse. var. *sudanense* Hitche), carrot (*Daucus carota* L. var. *sativa* D.C.), field bean (*Phaseolus vulgaris* L.), wheat (*Triticum aestivum* L.)
100-300	White clover (*Trifolium repens* L.), table beet (*Beta vulgaris* L.), alfalfa (*Medicago sativa* L.), radish *Raphanus sativus* L.), zucchini squash (*Curcurbita pepo* L. var. *Medullosa* Alef.)
>300	Swiss chard (*Beta vulgaris* L. var. *cicla* L.), tall fescue (*Festuca elatior* L.), cabbage (*Brassica oleracca* L. var. *capitata* L.), bermudagrass (*Cynodon dactylon* Pers.), tomato (*Lycopersicon esculentum* Mil.), paddy rice (*Oryza sativa* L)

a. Adapted from Bingham et al. [29,30]. Plant response observed for one particular kind of soil, and as such it is not necessarily applicable to all soils.

the soil with leaching water. For this reason, the boron concentrations may have a more immediate effect on restricting the use of wastewater for irrigation, and cumulative effects commonly important to other trace elements do not apply to B.

Large quantities of Mo may be added to the soil with little effect on crop growth [11]. However, Mo applied to the soil is readily absorbed by crops. The availability of Mo to crops increases with the soil pH. As a micronutrient element, Mo is required in small amounts by plants and is also essential, at low concentrations, in the diet of animals; for some livestock animals (particularly ruminant animals), however, Mo concentration as low as 5 mg/kg in the feed may be toxic [12]. Molybdenum toxicity and its severity are directly related to the amount of Mo ingested relative to that of Cu and SO_4. High Mo and low Cu levels in forage constitute the worst possible situation. Since more than 50% of the effluents from POTW may have Mo concentrations exceeding the upper limit of the irrigation-water-quality criteria, the potential hazard associated with Mo accumulation in plant tissue should be carefully evaluated when wastewater is to be used for irrigating forage crops or grazing pastures.

BEHAVIOR OF WASTEWATER-BORNE TRACE ELEMENTS IN THE SOIL

Passage of wastewater through the complex soil matrix induces a variety of physical and chemical reactions that influence the capacity of soil to renovate the wastewater. The mechanism of removal depends on the characteristics of trace elements in the wastewater. Trace elements present in the wastewater in suspended forms are removed primarily through filtration [13]. For all practical purposes, the suspended solids are expected to be deposited near the surface of the soil profile during irrigation with wastewater.

For trace elements present in the wastewater in the dissolved state, filtering would have no effect on their removal from the water. Instead, chemical reactions such as ion exchange, precipitation, surface adsorption, and organic complexing are important. Unless the equilibrium constants of each reaction are known, and the reaction kinetics in the soil are clearly defined, the outcome is unpredictable. Factors that influence the transformation of trace elements in the soil are illustrated in Figure 13-1.

The principal mechanisms that immobilize dissolved trace elements in the wastewater within the soil appear to be adsorption and precipitation. Recent studies have demonstrated that most soils have a high capacity to retain most trace elements [14-21].

At Pb application rates up to 3200 kg/ha [as $Pb(OAc)_2$], Stevenson and Welch [22] observed the downward movement of Pb in a midwestern soil to a depth not greater than 0.9 m. Doner [18] leached a Hanford soil with solutions containing 10 mg/L of Cd, Cu, or Ni and found that the soil had the capacity to attenuate 506, 558, and 1480 kg/ha of Cd, Cu, and Ni, respectively, before a breakthrough took place at the 30-cm depth.

Factors that affect the retention of trace elements by soils include soil texture, pH, soil organic matter, and contents of amorphous oxides of Fe, Al, and Mn. Fuller and co-workers [19,20,21], in a study of trace-element attenuation in a variety of soils found that all soils studied showed high capacity to attenuate the concentration of Cu and Pb in the soil solution. The retention of other trace elements studied was best correlated with the clay content and free iron oxide content of the soil. Capacities for attenuating the cationic trace elements (Cu, Pb, Be, Zn, Cd, Ni, and Hg) in soils tended to increase with their clay and iron oxide contents. For the anionic trace elements (SeO_3, VO_3, AsO_4, CrO_4), retention in the soil also increased with increasing clay and iron oxide content of the soils. Similar observations have been reported by other researchers [23]. In general, the solubility of cationic trace-element species increases as the pH of the soil decreases. By contrast, the solubilities of anionic trace-element species in the soil tend to increase as the pH of the soil increases.

The amounts of trace elements removed by crops are small compared with the amounts applied to the soils through the application (at 4 ft/year) of a wastewater with typical trace-element concentrations (Table 13-5).

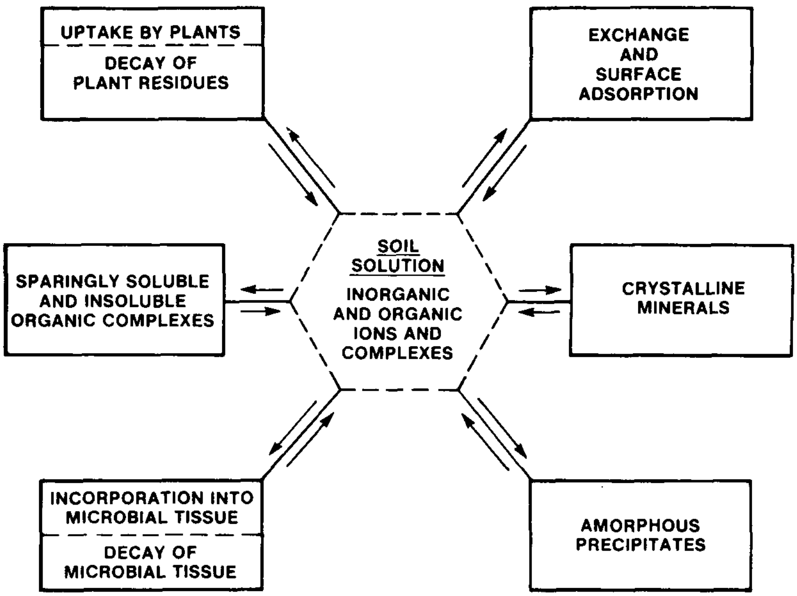

Figure 13-1. Schematic diagram showing possible pathways of trace elements in soils.

Table 13-5. Expected trace-element removal by vegetation from wastewater-irrigated soils.

Element	Typical concentration in wastewater[a] (μg/ml)	Annual input[b] (g/ha)	Typical concentration in vegetation[c] (μg/g)	Annual removal[d] (g/ha)	Removal (%)
As	<0.005	<60	1	5	8.3
B	1.0	12,000	50	250	2.1
Cd	0.005	60	0.5	2.5	4.2
Cr	0.025	300	0.5	2.5	0.8
Cu	0.10	1,200	15	75	6.3
Hg	0.0009	11	0.02	0.1	0.9
Mo	0.005	60	1	5	8.3
Ni	0.02	240	5	25	10.4
Pb	0.05	600	2	10	1.7
Se	<0.005	<60	0.5	2.5	4.2
Zn	0.15	1,800	50	250	13.9

a. From Dowdy, et al. [31].

b. At an application rate of 1.2 m/yr.

c. Authors 'estimates based on data from Bowen [25], Allaway [12], Chapman [28] and Lists [26].

d. Assuming annual dry-matter yield of 5 t/ha, e.g., potatoes.

Generally, no more than 10% of the added trace elements is expected to appear in the harvested crops. Long-term use of wastewater for irrigation, therefore, will result in their gradual accumulation in the affected soils.

CONCLUSIONS

When wastewater effluents are used for crop irrigation, the concentration of trace elements in the water is not high enough to cause any short-term acute harmful effects. Since most trace elements tend to accumulate in the soil, the trace-element contents of the receiving soil could be substantially elevated by the long-term use of the wastewater. Therefore, the potential for harmful effects in the future should not be overlooked. A typical wastewater may be applied for almost 100 years before any trace-element accumulation in the soil may reach a currently proposed upper limit for trace-element soil deposition. Since trace-element concentrations of wastewater vary considerably, it is essential that cropland irrigation operations should be evaluated case by case.

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CHAPTER 14

FATE OF WASTEWATER CONSTITUENTS IN SOIL AND GROUNDWATER: PATHOGENS

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INTRODUCTION

One major concern in using wastewater for agricultural irrigation is the potential public health hazard resulting from exposure to pathogenic organisms. The term "pathogenic" is applied to those organisms that invariably cause infectious diseases. Pathogens that can survive modern wastewater treatments include bacteria, protozoa, helminths (parasitic worms), and viruses. Epidemiological studies show that direct contact with these agents increases the probability of encountering gastrointestinal and urogenital infections. However, transmission of most pathogenic diseases from wastewater requires the fecal-to-oral route. There is very little evidence indicating a potential health hazard (by dissemination of infectious agents) in handling disinfected wastewater for irrigation on agricultural land [1].

FACTORS AFFECTING PATHOGEN SURVIVAL IN SOIL

In most cases, the survival rates of pathogens in soil have been reported to vary from a few hours to several months. A summary of pathogen survival rates in soils compiled by Gerba et al. [2], Parsons et al. [3], and Burge and Marsh [1] is shown in Table 14-1. Streptococci were reported to be viable for 35 to 63 days when applied to soil. Leptospira had survival rates of 15 to 43 days. Cysts of the protozoa *Entamoeba histolytica* remained viable for 6 to 8 days, and the survival time for tubercle bacilli was reported to be more than 180 days. Salmonellae may survive as long as 70 days in moist soil irrigated with wastewater and for 35 days in dry soil during the summer [4]. Hookworm larvae and enteroviruses have been reported to survive in soil for 42 days and for 8 to 175 days, respectively. Wellings et al. [5] showed that the survival of polioviruses in a

Table 14-1. Survival of pathogens in soils.[a]

Organism	Survival time (days)
Coliforms	38
Streptococci	35 to 63
Fecal streptococci	26 to 77
Salmonellae	15 to > 280
Salmonella typhi	1 to 120
Tubercle bacilli	> 180
Leptospira	15 to 43
Entamoeba histolytica cysts	6 to 8
Enteroviruses	8 to 175
Ascaris ova	Up to 7 years
Hookworm larvae	42
Brucella abortus	30 to 125
Q-fever organisms	148

a. Adapted from Gerba et al. [2]; Parsons et al. [3]; Burge and Marsh [1]

Florida cypress dome used for sewage effluent discharge was evident for at least 28 days. Lefler and Kott [6] reported the survival of poliovirus type 1 in dry sterile sand for 77 days. Tate and Terry [7] found a 92% and 86% decline in fecal and total coliform populations, respectively, as early as two days after a soil was amended with sewage effluent. Usually 2 to 3 months is sufficient time to allow the numbers of most pathogens in untreated wastewater to decline to negligible levels in soil after application [2]. However, survival of enteric bacteria in soil is dependent on several factors, including soil moisture content, temperature, pH, season of the year, sunlight, organic matter content, and antagonistic organisms [8].

Several reports indicate that increased soil moisture content tends to increase the survival rate of enteric bacteria. Beard [9] reported that the survival of *Escherichia coli* and *Salmonella typhosa* were increased substantially in moist soils. Kibbey et al. [10] found that the survival rate of *Streptococcus faecalis* was greatest when the soil was saturated and lowest when soil was air-dried. Boyd et al. [11] reported a decrease in microbial survival rates with a decrease in moisture content from 50% to 10% in a fine sandy loam soil. Survival time is less in sandy soils than in soils with greater water-holding capacities [2].

Survival of bacteria in soils is favored by cold temperatures [2]. Beard [9] reported that *S. typhosa* could survive as long as two years under freezing conditions. By increasing the temperature, the survival rates of enteric bacteria in soil tend to decrease. With a compilation of pathogen survival data from the literature, Reddy et al. [12] reported that the die-off rates of pathogenic bacteria and indicator organisms approximately double with an 18°F (10°C) rise in temperature between 41 and 86°F (5-30°C). The alternate freezing and thawing periods in the winter months also affects the survival of pathogens in soil: Weiser and Osterud [13] reported that freezing and thawing promoted significant mortality of *E. coli*.

Extreme acidic and alkaline conditions (pH < 6.0 or > 8.0) tend to adversely affect most bacteria in soil. Generally, neutrality (pH 7.0) favors the growth and survival of enteric bacteria. The pathogens *Erysipelothrix, Salmonella, E. coli, S. faecalis,* and *Mycobacterium* survive best at a soil pH range of 6 to 7 [14]. Die-off rates of these pathogens were higher under acidic soil conditions.

The season of the year influences the viable population of pathogens in soil. Their survival rates appear to be related to fluctuations in moisture and temperature. Van Donsel et al. [15] studied the death rates of *E. coli* and *S. faecalis* subsp. *liquefaciens* in soil with seasonal changes. They found a 90% reduction rate in fecal coliforms after 3.3 days in the summer and 13.4 days in the autumn. Fecal coliforms survived slightly longer than the fecal streptococci in the summer, but the reverse was true in the spring and winter months. In the temperate regions, both the autumn and spring months favor the survival of fecal coliforms and fecal streptococci, whereas populations diminish in the dry summer months [2,15].

Sunlight exerts a lethal effect on all microorganisms located on the very surface of soil. This effect may be due to desiccation and/or ultraviolet (UV) irradiation. Tannock and Smith [16] studied the survival of *Salmonella typhimurium* and *Salmonella bovismorbificans* applied to pasture soils exposed to direct sunlight vs. shaded areas. Two outdoor plots were exposed to direct sunlight, while two others were enclosed on three sides by black polyethylene sheeting approximately 1 m in height. In general, survival of salmonellae was prolonged in the shaded areas when compared with the exposed plots. In the summer, survival of *S. bovismorbificans* was evident up to 6 weeks after inoculation in the shaded areas and up to only 2 weeks in the direct sunlight. Similar results were reported by Van Donsel et al. [15]. When *E. coli* and *S. faecalis* were added to soil plots, their die-off rates were much greater when exposed to direct sunlight than when in shaded areas. The die-off rates of *Leptospira, Brucella,* and *Mycobacterium* are also influenced by the intensity of sunlight [2].

Bacterial numbers are generally related to the organic matter content of soil. Since the enteric bacteria are heterotrophs, their only carbon supply would be the organic nutrients present in soil and suspended organic material added with the wastewater. Geldreich and co-workers [17] enumerated coli-aerogenes bacteria from 251 soil samples collected from 26 states and 3 foreign countries and found that fecal coli-aerogenes were usually absent or present in comparatively low numbers in undisturbed soils. Tannock and Smith [16] reported that when surface water was contaminated with feces and applied to soil, salmonellae numbers declined by 10,000-fold in about 10 weeks, but when the feces were absent, a 1 million-fold decrease was observed within 2 weeks. Although both *Shigella* and *Salmonella* are capable of utilizing the limited carbonaceous materials in soils, they are not able to compete with the indigenous soil microflora for the low available nutrient supply [2]. Enteric bacteria require simple sugars for a carbon source to synthesize amino acids, nucleic acids, and vitamins, but simple sugars rarely exist in soil in the free form. Instead, carbohydrates are often complexed as polymers.

Antagonistic microflora may also effect the survival of pathogens introduced to soil by the means of wastewater. The survival time for enteric bacteria inoculated into sterilized soil is longer than that in nonsterile soil [2]. Predation by protozoa and parasitism by *Bdellovibrio* (bacteria which are parasites on other bacteria) may play a role in regulating bacterial populations. Production of lytic enzymes and antibiotics by soil fungi and actinomycetes could suppress the growth of enterics. Bryanskaya [18] reported that the growth of *Salmonella* and dysentery bacilli were inhibited by the present of actinomycetes in soils.

There is very little information available on the survival of helminths and protozoa in soil. Helminth ova can appear in sewage sludge and treated wastewater after sewage treatment practices. According to Burge and Marsh [1], the ova of *Ascaris lumbricoides* (intestinal worm) may survive as long as 7 years in a garden soil (Table 14-1). The survival and persistence of protozoa in wastewater and soil is usually attributed to their ability to form cysts, which is an inactive metabolic state that can endure extreme environmental conditions such as high and low temperatures, drought, adverse pH, and low oxygen concentrations. Cysts of the protozoan *Entamoeba histolytica* have been reported to survive up to 8 days in soil and up to 3 days on plant surfaces (Table 14-1).

Many viruses survive modern wastewater-treatment practices, including chlorination [2]. When wastewater is applied to soil, viruses may survive a year or more. Most of the studies on virus survival or inactivation in wastewater and soil have been carried out with polioviruses and bacteriophages (viruses which infect bacteria).

Virus inactivation (loss of infectivity toward the host cell) appears to be affected by dispersion of viral aggregate clumps, presence of salts (particularly chloride anions), temperature, pH, virucidal chemical species, and the presence of suspended solids [19]. Virus inactivation rates tend to be much greater in wastewater and natural waters than in distilled water because of disaggregation of viral clumps. Dispersion of poliovirus type 1 was more complete in secondary sewage effluent than in distilled water [20]. Burge and Enkiri [21] reported that the inactivation rate for øx-174 phage in sterilized soil leachate was 24 times greater than that of poliovirus type 1 in distilled water.

The presence of salts (NaCl) increases virus inactivation relative to non-saline environments; however, this effect can be partially reduced by the presence of divalent cations such as Ca^{2+} and Mg^{2+}. These cations have a stabilizing effect on viruses that prevents inactivation, particularly at elevated temperatures (50°C).

Studies on inactivation of viruses in relation to temperature and pH demonstrate that virus inactivation increases with increasing temperature [19], and permanent inactivation of enteroviruses in solution is favored by alkaline pH [22].

Antagonistic microflora in soil may produce inactivating agents such as antiviral toxins. Also, sterilization or heat treatment of wastewater may drive off heat-labile virucidal chemical agents such as ammonia [23].

Suspended organic matter and clay are believed to have some protective effect on viruses in wastewater. Bitton and Mitchell [24] reported increased survival rates of T7 phage in seawater containing colloidal montmorillonite. Gerba and Schaiberger [25] showed that viruses adsorbed to kaolinite clay survived longer in seawater than unadsorbed viruses.

Although there is a voluminous amount of literature on the removal efficiency and movement of viruses in soil, there has been very little work on virus survival in field experiments. Wellings et al. [5] reported that virus survival in a Florida cypress dome used for sewage effluent discharge was evident for at least 28 days. Fujioka and Loh [26] reported that poliovirus type survived in field plots at least 32 days when irrigated with wastewater effluent. Depending on the nature of the soil, temperature, pH, and moisture content, enterovirus survival has been reported to vary between 25 to 170 days [2].

It should be emphasized that the disappearance of infectious viruses from percolating wastewater occurs mainly by sorption interactions, but, this mechanism does not eliminate infectivity for host cells. Schaub et al. [27] reported that viruses adsorbed to clay were just as infectious to mice as were the free entities. Further, Lefler and Kott [6] demonstrated that viruses adsorbed to sand are capable of infecting tissue cultures.

MOVEMENT OF BACTERIA IN SOIL

The migration of wastewater pathogens in soil involves transport by insects, birds, rodents, overland runoff, windblown soil, and percolation through the soil profile to ground water. Many insects, birds, and rodents can become carriers of fecal agents when in direct contact with wastewater. However, there is no evidence that suggests dissemination of infectious agents by such means should be of major concern. Retention of pathogenic organisms near the surface could be a potential problem because of contamination of surface runoff waters and windblown soil, but treated wastewater would probably be of little threat. These mechanisms of transport are more likely to be applicable to livestock grazing areas and feedlots, since they appear to be concentrated with fecal coliforms and streptococci [28, 29, 30].

The main factors limiting transport of bacteria, ova of intestinal worms, and cysts of protozoa through the soil matrix are straining, sedimentation, and adsorption. The soil acts as a filter, and as the soil aggregates become disturbed, structural breakdown gives rise to swelling, slaking, and dispersion of soil particles straining even finer particles. The removal of bacteria, ova, and cysts from percolating wastewater, through a given depth, is inversely proportional to the soil particle size [31].

The infiltration rates of wastewater in soil influences the removal efficiency of pathogenic bacteria. Low flow rates favor greater retention in soils. The flow rate is dependent on soil texture, structure, type of clays present, and nutrients supplied by the wastewater to the indigenous soil microflora [32]. If wastewater is continuously applied to the soil, the nutrients may support continuous growth of the microflora, resulting in biological clogging and alteration in pore configuration.

Adsorption also plays a role in retention of bacteria by soil, but probably to a lesser extent than the previous factors mentioned. Goldschmid [33] showed that tapwater increased the removal of coliforms through sand when compared with distilled water. The removal efficiency of bacteria was increased with increasing cation concentration, higher valence, and decreasing pH (below pH 7.0). A more detailed explanation on the mechanism of adsorption will be presented in the discussion of virus movement in soils.

Several studies have shown that as much as 90% to 95% of the fecal organisms are concentrated in the surface layers during the passage of wastewater through soil, and the remainder are concentrated in subsurface layers [34, 35, 36, 37]. Information on the movement of pathogenic bacteria through soil in relation to wastewater application has been compiled by Gerba et al. [2] and Hagedorn et al. [38] and is shown in Table 14-2.

The Sanitary Engineering Research Laboratory of the University of California at Berkeley initiated the first major field studies at Whittier and Azusa, California, on bacterial removal during wastewater percolation through soil. At the Whittier Narrows Recharge site, coliform densities in secondary sewage effluent were reduced from 110,000 to 40,000 per mL after percolating through infiltration basins with a 3-ft (0.9-m) depth in 12 days [39]. At Azusa, a depth of 2.5 to 7 ft (.8 to 2.1 m) of soil was required to reduce the density of 120,000/100 mL in treated sewage effluent to 6,000 organisms [40]. In Lodi, California, secondary sewage effluent was allowed to percolate

Table 14-2. Movement of bacteria through soils in relation to wastewater application.[a]

Nature of fluid	Organisms	Media	Maximum distance traveled (m)	Time of travel
Tertiary treated wastewater	Coliforms	Fine to medium sand	6.1	--
Secondary sewage effluent on percolation beds	Fecal coliforms	Fine loamy sand to gravel	9.1	--
Primary sewage in infiltration beds	Fecal streptococci	Silty sand and gravel	183	--
Inoculated water and diluted sewage injected subsurface	*Bacillus stearothermophilis*	Crystalline bedrock	28.7	24-30 hr
Sewage in buried latrine intersecting groundwater	*Bacillus* coli	Sand and sandy clay	10.7	8 weeks
Canal water in infiltration basins	*Escherichia coli*	Sand dunes	3.1	--

a. Adapted from Gerba et al. [2]; Hagedorn et al. [38].

through sandy loam soil for 2½ years. Results indicated that the most probable number of coliform bacteria was reduced from 10^5 to less than one per mL of effluent in 4 to 5 ft (1.2 to 1.5 m) of soil [41].

The Santee Water Reclamation Project near San Diego, California, involved the application of tertiary treated sewage effluent through percolation beds consisting of a shallow stratum of sand and gravel [42]. Analysis of total coliforms, fecal coliforms, and fecal streptococci in water samples was performed on sample well sites 200 ft (61 m) and 400 ft downstream from the percolation beds and 1500 ft (457 m) downstream in a collection ditch. Most of the bacteria were removed within the first 200 ft of travel. Fecal streptococci densities were reduced from 4,500/mL in the sewage effluent to 20, 48, and 7/mL when sampled downstream in the 200-ft and 400-ft wells and the collection ditch, respectively.

The Flushing Meadows Wastewater Renovation Project near Phoenix, Arizona, has been recharging groundwater since 1967 with an activated-sludge-type secondary sewage effluent and has proved to be highly successful in obtaining favorable bacterial quality in the renovated water [43]. The effluent was allowed to infiltrate into six parallel horizontal basins (6 m by 210 m, 6 m apart) consisting of 6 to 9 m of fine loamy sand underlaid by a succession of coarse sand and gravel layers to a depth of 75 m. The infiltration rate was approximately 330 ft (100 m) of wastewater per year. Renovated well water samples contained no human viral pathogens nor salmonellae, and the numbers of fecal coliforms, fecal streptococci, and total bacteria were reduced by 99% after the wastewater was filtered through approximately 30 ft (9 m) of soil.

MOVEMENT OF VIRUSES IN SOIL

Virus removal from percolating wastewater is almost totally dependent on adsorption to various soil components. Excerpts from the literature on the movement of viruses through various soil systems is shown in Table 14-3.

Drewey and Eliassen [44] conducted experiments on virus migration with bacteriophages T1, T2, and f2 through nine California soils varying widely in chemical and physical properties. Batch tests

Table 14-3. Movement of viruses through soil.[a]

Virus type	Nature of fluid	Nature of medium	Flow rate	Distance of travel	Percentage of removal
T1, T2, f2	Distilled water with added salts	9 types of soils from California	0.078 mL/min to 0.313 mL/min	45 to 50 cm	> 99
Poliovirus 1	Distilled water, 10^{-5} $\underline{N}$ Ca and Mg salts	Dune sand	1 mL/min to 2 mL/min	20 cm	99.8 to 99.9
Poliovirus 2	Distilled water	Low humic latersols	100 gal/day·ft^2 to 140 gal/day·ft^2	1.5 to 6 inch	96 to 99.3
Poliovirus 2	Secondary effluent	Sandy gravel	--	60 m	100
Coxsackie	Spring water	Garden soils	--	36 inch	50
T4	Distilled water	Low humic latersols	100 gal/day·ft^2 to 140 gal/day·ft^2	1.5 to 6 inch	100
T7	Secondary treated	Sandy forest	--	19.5 cm	99.6
Indigenous enteric viruses	Secondary effluent	Loamy sand soil	Intermittent avg: 0.02 cm/min	3 to 9 m	100

a. Adapted from Bitton [52]; Gerba et al. [2]; Vilker [19].

revealed that T2 and f2 followed typical Freundlich isotherms, indicating physical adsorption. In column experiments, viruses were suspended in distilled water and passed through sterile soil columns. Over 99% of virus removal was demonstrated with radioactive tagging (P-32), indicating that most of the viruses were retained in the upper 0.8 inch (2 cm) of the columns.

Robeck et al. [45] conducted studies on poliovirus removal through 2 ft (0.6 m) of California dune sand at application rates of approximately 20 to 40 gal/ft^2·day (0.8 to 1.6 m/day). Results indicated that the sand was capable of removing 99% of the viruses in 98 days. At the Santee Project (near San Diego), high concentrations of attenuated (reduced virulence) polioviruses were applied to percolation beds consisting of sand and gravel. Poliovirus could not be detected downstream in sample wells 200 ft (61 m) from the application site.

In 1974, at the Flushing Meadows Project, secondary sewage effluent and renovated water from four well sites were assayed for viruses periodically every two months [43, 46]. Virus doses in the sewage effluent ranged from 158 to 7,475 plaque-forming units (PFU) per 100 L with seven different types of viruses identified. Wastewater viruses did not move through the soil infiltration system into the groundwater and were adsorbed by 9.8 to 29.5 ft (3 to 9 m) of basin soil with a 99.99% removal efficiency.

Lance et al. [47] studied virus movement in 250-cm columns packed with calcareous sand flooded with secondary sewage effluent containing about 3×10^4 PFU of poliovirus type 1 (LSc) per mL. The viruses were suspended in dechlorinated secondary sewage effluent and applied to soil columns on a schedule of 9 days of flooding alternated by 5 days of drying. Movement through the soil reduced the virus concentration to about 1% of the initial level during the first 2 cm of travel and to 0.1% after 38 cm of travel. Viruses were not detected in 1-ml extracts from columns below 160 cm.

Landry et al. [48] studied adsorption and elution of human enteroviruses in permeable sandy soil cores (43 by 125 mm) collected from an operating recharge basin on Long Island. The viruses studied included field strains and reference strains of poliovirus types 1 and

3, coxsackie virus B3, and echovirus types 1 and 6. The viruses were suspended in treated sewage effluent and allowed to percolate through soil cores. Infiltration rates for all cores were rapid, averaging 83 cm/hr. Column effluents were collected and assayed for total virus PFU. All the polioviruses tested (including field and reference strains) and coxsackie B3 were adsorbed extremely well. Echovirus 1 exhibited the greatest soil affinity (over 99%), whereas echovirus 6 showed the least affinity with 78% of virus adsorption.

Wang et al. [49] recently conducted laboratory experiments on the effects of soil permeability on virus removal through soil columns. Unchlorinated secondary sewage effluent seeded with poliovirus type 1 or echovirus type 1 was continuously applied to 100-cm soil columns for 3 to 4 days at various hydraulic flow rates. Column effluents at various depths were assayed for virus PFU. The effectiveness of virus removal was influenced by the soil types and the hydraulic flow rates. Their results indicated that virus removal was very effective at a flow rate of 13 inches/day (33 cm/day). A soil depth of 2.8 inches (7 cm) was sufficient to remove these two viruses in a sandy loam soil, whereas 47 and 67 cm were required to remove more than 98% of the seeded viruses from Flushing Meadows and Pomello sands, respectively.

FACTORS AFFECTING VIRUS REMOVAL BY SOIL

The mobility of viruses in soil is related to the properties of the viral protein coat; to the cation exchange capacity, pH, hydraulic conductivity, surface area, organic matter content, and texture of the soil; and to the pH, the ionic strength, and the flow rate of the percolating fluid. Viruses are colloidal-size particles (10-300 nm) that possess a nucleic acid core encapsulated by a shell or capsid (sometimes the capsid is enclosed by an envelope). The morphological feature of the protein coat (which includes the capsid and lipoprotein envelope) is characterized by being amphoteric. Soil organic matter and clay are generally negatively charged and readily adsorb the positively charged reactive groups of the viral protein coat below its isoelectric point (the pH in which there is no electrical charge on the particle). Cookson [50, 51] studied the mechanism of adsorption of bacteriophage T4 to activated carbon and found that the adsorption process was reversible and obeyed linear adsorption isotherms. The mechanism of adsorption was believed to involve the positively charged amino groups of the T4 phage and the negatively charged carboxyl groups of the activated carbon particles. When the pH of the medium was lowered, the carboxyl groups became protonated and desorption was evident.

Bitton [52] reviewed the mechanism of sorption between viruses and surface particles and reported that the presence of cations in the medium greatly influences the adsorption process. Cations of various salts neutralize the repulsive electrostatic potential of excess negative charges of the virus and soil colloids. Lefler and Kott [6] reported that the retention of poliovirus type 1 in sterile sand columns was increased in the presence of 0.5 N NaCl. Divalent cations are much more effective for the adsorption of viruses to surface particles when compared with monovalent cations [53, 54].

Gerba and co-workers [2] reviewed two theories on the mechanism of virus adsorption to soil. One theory involves the virus-cation-clay bridge, in which the cation links the two negatively charged particles. Reactive groups of viral proteins such as charged carboxyl, sulfhydryl, and phenolic OH groups are responsible for the electrostatic attraction between the viruses and the adsorbed cations held by micelles (minute colloidal particles) in the cation exchange sites of soils. If the concentration of cations in solution is reduced, the bridging effect breaks down and the virus is eluted. The other theory involves the fixation of cations onto ionizable groups of the viral particles, reducing the net electric charge and allowing an interaction with surface particles by Van der Waals forces.

Until recently, most of the literature reported on virus removal in soil was on a limited number of virus types. Goyal and Gerba [55] compared adsorption of 27 different types and strains of human enteroviruses and bacteriophages to nine different soil types using a 30-min batch adsorption procedure. Virus adsorption to soil was highly strain-dependent. Of all the viruses tested, poliovirus type 1 and coliphage T4 were adsorbed most readily to the nine soils. Echovirus type 1 and coliphage f2 were adsorbed the least. The work showed that no single enterovirus or coliphage should be used to model virus adsorption behavior to soils. Differing adsorption patterns for various virus strains appears to be due to their characteristic viral capsid protein affecting the viral isoelectric point and electronegative charge [48].

There have been many attempts to predict the ability of a soil to adsorb virus particles based on the chemical and physical properties of the soil (Table 14-4). Virus adsorption is generally enhanced with increasing clay and organic matter content because of their surface area and greater number of active sites for adsorption compared with silt and sand. Burge and Enkiri [21] found that, of all the soil properties which show general trends to increasing levels of adsorption (pH, cation exchange capacity, surface area, glycerol-retention capacity, and organic matter content), only pH was significantly correlated with the rate of virus adsorption. However, Gerba and Lance [56] reported that virus adsorption was highly dependent on the CEC and exchangeable aluminum content of soils.

Virus adsorption is generally favored at pH values below 7.0 and is less effective at higher pH values [44]. Landry and co-workers [48] reported that a soil pH below 5.0 seems to be the best for adsorbing a wide variety of enteroviruses. In general, viruses are negatively charged at a pH above their isoelectric point, behaving as an anion and repelling the negatively charged soil particles. At a pH below the viral isoelectric point, the virus would behave as a cation with greater attraction to the negative micelles. The isoelectric point for most enteric viruses is below pH 5.0 [2]. However, a low pH may not favor best wastewater irrigation practice, since inactivation of enteroviruses is favored by alkaline pH [22].

Evidently, organic compounds are able to compete with viruses for adsorption sites on soil colloids [53]. Schaub et al. [57] reported that when soils were treated with wastewater containing low cation and high soluble organic concentrations, viruses were not adsorbed effectively because of the electronegative charges on both the viruses and low-molecular-weight organic material. Consequently, viruses remaining in primary sewage effluent are poorly held by soil compared with those in secondary effluent [47].

Table 14-4. Factors affecting virus removal by soil.

Factors	Remarks
pH	Low pH favors virus adsorption; however, high pH favors virus inactivation.
Cations	Cations neutralize or reduce the repulsive electrostatic potential (negative charge) of virus particles and soil components, favoring adsorption.
Clays	Enhances virus adsorption.
Organic matter content	Enhances virus adsorption.
Cation exchange capacity	High cation exchange capacity promotes virus adsorption.
Flow rate	Low flow rates (<0.6 m/day) favor virus removal.
Suspended solids	Soluble organic matter competes with viruses for adsorption sites on soil colloids and hinders viral inactivation in wastewater.
Rainwater	Promotes desorption of viruses.

Lance and Gerba [58] reported that the velocity of wastewater movement through soil is an important factor affecting virus distribution with depth. They found that when flow rates of secondary sewage effluent seeded with poliovirus type 1 were increased from 0.6 to 1.2 m/day, more virus movement occurred through the soil. Flow rates less than 0.6 m/day were the most effective for virus removal. At the Flushing Meadows field site, 90% to 99% of the applied poliovirus type 1 in secondary sewage effluent was removed in the upper 2 to 4 inches (5 to 10 cm) of soil at infiltration rates of 6 to 22 inches/day (15 to 55 cm/day) [47]. Robeck et al. [45] reported that virus removal in coarse sands was more than 90% when flow rates were less than 3 ft/day (0.9 m/day). More virus breakthrough was observed as the rate was increased, reaching 80% to 90% elution at flow rates above 192 ft/day (59 m/day).

Mobilization of viruses in soil is affected not only by the flow rate of wastewater but also by the ionic strength of the percolating fluid. Viruses are slightly negatively charged at the pH often encountered in wastewater [19]. The presence of cations will neutralize the repulsive interaction between the viral particles and soil colloids. The divalent cations (Ca^{2+} and Mg^{2+}) appear to be more effective than monovalent cations (Na^{+}, K^{+}), and trivalent cations (Al^{3+}, Fe^{3+}) are even more efficient in forming a virus-cation-clay bridge. Goyal and Gerba [55] found that adsorption of coxsackie virus strains were enhanced to the Flushing Meadow soil by the presence of 10 mM Ca^{2+}. Lance and Gerba [58] observed complete adsorption of poliovirus type 1 (LSc) in the top 5 cm of soil when 5 mM of $CaCl_2$ was added.

Intermittent loading of wastewater to soil tends to enhance virus immobilization over continuous loading. Lance et al. [47] found that drying the soil for one day between virus loading and flooding with deionized water reduced migration of viruses through soil columns. Upon flooding, elution of viral particles was not observed after a 5-day drying period. Furthermore, wetting and drying cycles of 14 days at the Flushing Meadows project site resulted in very high virus retention in soils. There appears to be no conclusive reports on how wetting and drying affects virus inactivation.

Virus desorption can be demonstrated when the ionic strength of the percolation fluid is lowered. Duboise and his associates [59] reported adsorption of poliovirus in soil columns when sewage effluent was applied, but the addition of distilled water caused the release and migration of the virus through the columns. Roper and Marshall [60] showed similar findings when a bacteriophage from marine sediments was rapidly desorbed following decreasing salinity with successive washings of the samples. Lance et al. [47] reported that when deionized water was applied 2 hours after a sewage-water-poliovirus 1 mixture was added to soil columns, desorption of viruses eluting down to 5.2-ft (160-cm) depths was evident. Increased virus elution from soil cores often coincides with low electrical conductivity levels of column effluents [59]. In the field, heavy rainfall could cause desorption of viruses and promote their downward migration to the groundwater. Wellings et al. [5] observed a burst of enteric viruses in 3-m sampling wells following a period of heavy rainfall.

SUMMARY

The survival rates of pathogenic bacteria in soil normally vary from one day to several months. Many factors affect the survival of enteric bacteria in soil. Increased soil moisture content, cooler temperatures, and higher organic matter content tend to favor longer survival, but extremely acidic or alkaline conditions, sunlight, and antagonistic microflora are opposing factors to survival. Protozoa and helminths appear to survive as long as enteric bacteria in soil, although ascaris ova may remain viable much longer. Depending on the nature of the soil, temperature, pH, and moisture content, enterovirus survival has been reported to vary from 25 to 170 days. Virus inactivation is promoted by dissaggregation of viral clumps, presence of chloride salts, high temperature and pH, and virucidal chemical species such as ammonia. Suspended organic matter in wastewater (virus-solid association) is believed to have some protective effect on virus survival.

The movement of pathogens in soil involves transport by insects, birds, rodents, windblown soil, overland runoff, and percolation through the soil profile to groundwater. Continuous application of wastewater could result in accumulation of pathogens at the soil surface. Pathogen movement in surface runoff water may be a greater hazard for disseminating diseases than pathogen elution to groundwater. The main factors that govern the transport of bacteria, ova of intestinal worms, and cysts of protozoa through the soil matrix are straining, sedimentation, and adsorption. Most studies show that bacteria are confined to the upper few centimeters of soil and never reach the groundwater unless the soil has large cracks or channels.

The literature indicates excellent removal of viruses through soil columns and adsorption in batch studies. It is evident that viruses differ quite markedly in their survival and removal during percolation through soil. The mobility of viruses in soil is related to viral properties; to the pH, cation exchange capacity, surface area, organic matter content, and texture of the soil; and to the pH, ionic strength, and flow rate of the percolating fluid.

Adsorption is the primary mechanism for viral retention in soil and is favored by low flow rates, intermittent loading, high cation exchange capacity, high clay content, high organic matter content, and low pH. Desorption is promoted by percolating fluids with low ionic strength through soil. Wastewater application to soil appears to be very effective in pathogen immobilization and inactivation.

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CHAPTER 15

FATE OF WASTEWATER CONSTITUENTS IN SOIL AND GROUNDWATER: TRACE ORGANICS

A. C. Chang and A. L. Page

INTRODUCTION

Organic matter content of wastewater and its treated effluents is customarily expressed in terms of the biochemical oxygen demand, the chemical oxygen demand, and the total organic carbon. Although these measurements have been effective in estimating the pollutional strength of the water and evaluating the performance of wastewater treatment processes, they neither indicate the composition of organic matter nor identify any toxic organic substance. It is quite conceivable that two waters of identical total organic carbon contents may be composed of entirely different organic compounds. In the toxicological assessment of the water quality, it is essential that toxic organic substances in the water be positively identified and their concentrations determined.

Analytical techniques now permit the identification and detection of organic chemicals in the water at concentrations near the level of one part per billion [1,2]. Although these methods are rather cumbersome for routine water-quality monitoring, they have been helpful in understanding the chemical nature of organic substances in the water. When these improved analytical procedure are used, a wide spectrum of organic chemicals in minute quantities are isolated from surface water bodies, ground water, and drinking water [3,4]. The majority of the organic residues found in the water are naturally occurring. But many synthetic organic compounds also are known to be toxic or are suspected of causing cancer on the basis of short-term laboratory tests. The concentrations of these substances in the water, except in rare instances, are always below levels at which adverse responses have been reported. Their presence in the water, nevertheless, raises the possibility that the long-term low-level exposure to potentially harmful organic substances through the use of water may become a human health hazard. In municipal wastewater, organic chemicals similar to those present in natural water systems have been found even more frequently.

One of the most important routes for chronic exposure to trace quantities of hazardous organic chemical (--the direct ingestion of the substance through drinking water--) was examined by a panel of experts assembled in 1976 by the National Academy of Sciences and National Academy of Engineers [5]. They reviewed the existing scientific literature for information relevant to the occurrence, metabolism and toxicology of each potentially hazardous water-borne organic substance. There is a serious deficiency of toxicological data for organic compounds and a great deal of uncertainty associated with extrapolating those data to assess the risk of low-level chronic exposure. However, they found no evidence that trace amounts of toxic organic substances in drinking water have caused cancer or increased the incidences of cancer. Since the no-response threshold concentration cannot be clearly established, the risk of disease as a result of long-term exposure cannot be completely ruled out.

In wastewater irrigation, the route of exposure to water-borne trace organics will not be direct ingestion. Instead, trace organics are deposited in the soil, subjected to attenuation by physical, chemical, and biological reactions in the soil, and translocated into plant tissue before they may enter the human food chain. Through the soil matrix, trace organics introduced by irrigation may also become contaminants of groundwater. It is essential that the fate of trace organic substances introduced into the soil through irrigation be determined.

OCCURRENCE OF TRACE ORGANICS IN WASTEWATER

In the current literature, the term "trace organics" is not clearly defined. Generally, the term is used to characterize those organic substances that are present in seemingly uncontaminated water or treated wastewater effluents in extremely low concentrations. Most of the constituents detected are perhaps naturally occurring, At the concentration levels in which they appear in water, none of them seriously interferes with use of the water. However, there are also many potentially toxic synthetic organic chemicals. Although there are thousands of synthetic chemicals, not all of them have found their way into the water. Some chemicals occur in water more frequently than others. The trace organic composition of any two streams of water are not likely to be the same. For the purpose of this discussion, only the potentially hazardous trace organics of the water will be considered.

Recently, the occurrence of priority pollutants in the influents of four publicly owned treatment works (Cincinnati, Ohio; Atlanta, Georgia; St. Louis, Missouri; and Hartford, Conn.) was surveyed [6]. "Priority pollutants" are toxic pollutants regulated under section 307 of the Federal Water Pollution Control Act, (see 95th Congress Committee Print 95-30 Data relating to H.R. 3199, U.S. Government Printing Office, 1977). Among them, 77 were never detected during the 3-month sampling period, and another 20 were detected less than 10% of the time. Of the 56 frequently found priority pollutants, 43 were organic substances. Many were found in extremely low concentrations. Table 15-1 summarizes the detection frequency, the range and the average concentrations of each organic priority pollutant. Since their concentrations in wastewater were low, it was often difficult to pinpoint their source. Although they were found in wastewater from both residential and industrial sectors of the urban community, the wastewater flow from the industrial area contributed significantly greater amounts to the total trace organic load [7]. However, it is not certain that the pattern developed from the wastewater of these communities could be extrapolated to represent the distribution pattern of trace organics in the 13,000 publicly owned treatment works in the United States; nevertheless, this represents the best available data.

Processes commonly engaged in the treatment of the municipal wastewater are designed to remove suspended solids, biochemical oxygen demand, and bacteria from the incoming wastewater. Studies show that conventional wastewater treatment is also effective in reducing the level of trace organics [7]. The removal of trace organics occurs almost entirely during biological treatment. Chlorination of wastewater effluent often yields additional halogenated hydrocarbons [8,9]. Although rapid sand filtration has little effect on the

Table 15-1. Priority pollutants in influents from publicly owned treatment works[a].

Priority pollutant	Frequency of detection	Concentration (µg/L) Range	Mean
Trichlorofluoromethane	6	--	--
Acrylonitrile	6	--	--
1,1-Dichloroethylene	17	0- 8.6	2.4
1,1-Dichloroethane	6	0- 0.3	0.1
trans-1,2-Dichloroethylene	28	0- 18.6	4.8
Chloroform	100	3.6- 7.1	4.9
1,2-Dichloroethane	11	0- 0.4	0.2
1,1,1-Trichloroethane	78	0.3- 95.9	28.9
Bromodichloromethane	11	0- 0.7	0.2
Trichloroethylene	67	0- 164.9	50.5
Benzene	67	0- 7.0	2.7
Dibromochloromethane	22	0- 1.0	0.2
1,1,2,2,-Tetrachloroethane	6	--	--
1,1,2,2-Tetrachloroethylene	83	1.1- 239.4	77.9
Toluene	78	1.6- 60.2	25.8
Chlorobenzene	6	0- 0.2	0
Ethylbenzene	67	0- 48.7	16.3
Phenol	33	0- 18.8	7.3
2,4-Dimethylphenol	11	0- 9.9	2.5
p-Chloro-m-cresol	6	--	--
Pentachlorophenol	22	0- 19.2	5.7
Dichlorobenzene	56	0- 92.7	33.1
Napthalene	44	0- 32.9	11.6
Diethylphthalate	50	3.6- 11.6	6.8
Di-n-butylphthalate	67	4.2- 15.8	9.3
Butylbenzylphthalate	44	0- 77.3	22.2
Bis(2-ethylhexyl)/ di-n-octylphthalate	22	0- 4.5	2.2
Heptachlor	6	--	--

a. Derived from Levins et al. [6].

concentrations of trace organics in the water, lime coagulation is an effective unit process for reducing the concentration of trace organics during tertiary treatment. However, even with activated carbon adsorption and reverse osmosis, a wastewater effluent is not rendered completely free of trace organics [10]. In one study, the concentrations of trace organics in a treated wastewater effluent usually followed a log-normal distribution. Table 15-2 summarizes the concentrations of trace organics of the secondary effluent at the Orange County Water District's wastewater treatment plant from 1976 to 1978 [10].

BEHAVIOR OF TRACE ORGANICS IN THE SOIL

Soils are porous media consisting of weathered mineral fragments, organic matter, microorganisms, water, and air. They are chemically and biologically complex. For the purpose of describing the behavior of trace organic substances in the soil environment, the physical features of a soil may be divided into four components:atmospheric, aqueous, solid, and biotic. The fate of a trace organic compounds during the passage of wastewater through the soil matrix is dependent on the partitioning of the introduced chemical among these four components. The mechanisms that are responsible for the attenuation of trace organics are essentially identical to those in other segments of the environment. However, the reaction kinetics that determine the mass transfer may be different from those in the aqueous or the atmospheric system. Experiences indicate that rate constants for the transport process in the soil are influenced by the properties of the soil and the nature of the chemical compound.

Among the processes that may affect the transformation of trace organic substances during wastewater irrigation, adsorption, volatilization, and biodegradation are considered most important. At present, there are few experimental data that would permit a comprehensive evaluation of the fate of trace organics in the soil. In the following discussion, one approach to assessing the behavior of trace organics in the soil is presented.

Table 15-2. Trace organics (μg/L) in secondary effluents--Orange County Water District.

Compound	Jan. 1976 - Sept. 1976[a] No. of samples	Range	Geometric mean	Mar. 1978 - Oct. 1978[b] No. of samples	Range	Geometric mean
Trihalomethane						
Chloroform	52	0.2 -3.9	1.6	28	0.8-17	2.9
Bromodichloromethane	42	<0.1 -1.1	0.09	27	0.2-3.2	0.6
Dibromochloromethane	35	<0.1- 10	0.15	28	0.2-1.8	0.71
Bromoform	24	<0.1- 3	0.12	23	0.1-6.4	0.37
Other volatile organics						
Carbon tetrachloride	--	---	--	28	<0.1-0.1	<0.1
Methylene chloride	41	1.7-74	17.0	--	---	--
1,1,1-Trichloroethane	50	<0.3-38	4.7	28	0.3-15	2.9
Trichloroethylene	46	<0.1-12	0.9	--	---	--
Tetrachloroethylene	39	<0.1-15	0.6	28	0.2-9.5	1.5
Chlorobenzenes						
Chlorobenzene	14	0.2 -9.4	2.5	27	<0.02-1.1	0.11
1,2-Dichlorobenzene	15	0.3 -8.9	2.4	27	0.07-13	0.63
1,3-Dichlorobenzene	15	0.2 -1.7	0.68	26	<0.02-5.4	0.17
1,4-Dichlorobenzene	15	0.8 -9.2	2.1	26	0.07-15	1.9
1,3,4-Trichlorobenzene	15	<0.02-4.1	0.46	27	<0.02-3.1	0.18
Aromatic hydrocarbons						
Ethylbenzene	13	0.2 -8.7	1.4	25	<0.02-0.5	0.039
m-Xylene	--	---	--	24	<0.02-0.2	0.027
p-Xylene	--	---	--	24	<0.02-0.04	0.016
Naphthalene	16	0.1 -4.1	0.57	27	<0.02-0.54	0.065
1-Methylnaphthalene	11	0.1 -3.9	0.86	27	<0.02-0.89	0.004
2-Methylnaphthalene	10	0.4 -2.6	1.0	27	<0.02-0.18	0.018
Solvent extractables[b]						
Dimethylphthalate	3	14.7-18.7	0.6	25	0.8-14	5.4
Diethylphthalate	11	<2	<2.0	25	<0.3-12	<0.3
Di-n-butylphthalate	3	<0.5- 0.5	<0.5	24	<0.5-3.4	0.75
Di-isobutylphthalate	11	<0.3-16	2.9	25	<1-10	4.4
Bis-[2-ethylhexyl]phthalate	11	15 -65	28.0	25	<4-62	9.3
PCB (as Aroclor 1242)	11	2 - 7.6	3.3	25	<0.3-1.3	0.47
Lindane	10	<0.1- 0.6	0.19	25	0.09-0.19	0.15

a. Period from Oct. 1976 to Mar. 1978 trickling filter effluent, period from Mar. 1978 to Oct. 1978 activated sludge treatement with segregation of wastewaters to reduce industrial inputs.

b. One liter of sample extracted with 2 x 15 mL of hexane, dried with sodium sulfate, concentrated to 2 mL, and cleaned on a Florisil column before analysis.

Adsorption

In the soil, adsorption is a process that describes the migration of chemical constituents from the aqueous phase to the surface of soil particles. As the solutes are temporarily or permanently immobilized into the stationary phase, the concentration of potentially hazardous trace organic substances in the soil solution will be reduced. Although a variety of intermolecular electrostatic forces are known to cause adsorption in soils, it is not always possible to measure the relative contribution of each interacting component in an adsorption process. As a result, the soil adsorption is always measured as the sum of contributing processes.

The distribution of a solute between the aqueous phase and the solid phase at equilibrium can be mathematically described by the Langmuir or the Freundlich adsorption isotherm. The experimentally obtained data may also be fitted into a simple proportionality equation [11]:

$$\frac{X}{M_s} = K_d \times C \qquad [15\text{-}1]$$

where X is the amount of solute adsorbed (μg), M_s is the amount of soil (g), C is the equilibrium solute concentration (μg/mL), and K_d is the soil adsorption constant (mL/g).

In this equation, the value of K_d, which indicates the relative magnitude of the adsorption, is specific for the soil and the chemical involved. For non-polar hydrophobic organic substances, their adsorption can be positively correlated to the organic matter content of the soil [12,13]. Therefore, Equation 15-1 may be written to express the influence of soil organic matter so that:

$$\frac{X}{M_{oc}} = \frac{K_d}{f_{oc}} \times C = K_{oc} \times C \qquad [15\text{-}2]$$

where f_{oc} is the soil organic matter expressed in weight fraction, M_{oc} is the amount of soil organic matter (g) that equals M_s multiplied by the fraction of soil organic matter (f_{oc}), and K_{oc} is the soil adsorption constant in terms of the soil organic matter (mL/g).

Under a given circumstance, the K_d is experimentally determined. The value of K_{oc} for a given organic substance, however, remains fairly constant and is independent of the soil type. Despite the importance of the adsorption constants in predicting the transport of organic solute in the soil, only a few K_{oc} and K_d values of trace organic substances (except for pesticide residues) have been determined.

More recent studies showed that the K_{oc} of an organic substance may be estimated from the octanol-water partition coefficient (K_{ow}) of the compound [14]. Several equations that may be used to empirically estimate the K_{oc} of trace organic substances are listed as follows:

$$K_{oc} = 0.63 \times K_{ow} \text{ [12]} \qquad [15\text{-}3]$$

$$\log K_{oc} = 0.72 \log K_{ow} + 0.49 \text{ [15]} \qquad [15\text{-}4]$$

$$\log K_{oc} = 0.544 \log K_{ow} + 1.377 \text{ [16]} \qquad [15\text{-}5]$$

The octanol-water partition coefficient (K_{ow}) describes the hydrophobicity of an organic compound by partitioning it between the aqueous phase and a phase (octanol) in which lipids are soluble [17]. It has been used extensively in predicting the chemical behavior of organic compounds in water and soil. Besides its usefulness in predicting the K_{oc}, the K_{ow} of a compound may also indicate the bioaccumulation potential in the aquatic environment. It appears that octanol is similar in polarity characteristics to the glyceryl esters that comprise the principal components of the cell membrane. More important, the K_{ow} of organic compounds are extensively tabulated. They may also be estimated from the molecular structure of the compound. The availability of K_{ow} in the published literature provided the basis for calculating the K_{oc} of selected trace organic substances of treated wastewater effluent shown in Table 15-3 [17,18,19]. The K_{oc} values of selected trace organic substances varied from 70 for bromodichloromethane to more than 30,000 for PCB. The strong adsorption of PCB by earth materials is well established [20]. Compounds with a K_{oc} of 200-300 or higher are expected to be effectively immobilized in the soil under most irrigation schedules (3 to 4 ft/year or 91-122 cm/year) [21,22].

Volatilization

In a moist soil, volatilization from the dilute aqueous solution is determined by the partitioning coefficient (K_w) between the water and the air [11,23]. The K_w of an organic chemical is defined as the ratio of the equilibrium concentration in water (µg/mL) to the corresponding concentration in the air (µg/mL) at 77°F (25°C). This parameter provides a comparative measurement of the ability of a chemical to partition between the water and the air. A lower numerical value of K_w indicates a greater tendency for the compound to become volatilized. Since a steady-state equilibrium is seldom reached in the soil, the partitioning coefficient of a compound between the water and the air in a soil is best determined experimentally.

If experimental data are not available, the partitioning coefficient may be estimated. Mathematically, the value of K_w for an organic chemical equals the inverse of the Henry's Law constant and can be approximated by dividing the water solubility (S in µg/mL) by the saturated vapor concentration (i.e., amount of the chemical in vapor phase [µg]/volume of gas [cm³]). Using the perfect gas law to evaluate the saturated vapor concentration, the K_w may be expressed as [11]:

$$K_w = [S \times 0.062366 \times (273.15 + T)]/[V_T \times M] \qquad [15\text{-}6]$$

where S is the water solubility of the organic chemical (µg/mL), T is the temperature (°C) at which the water solubility was measured, V_T is the saturated vapor pressure at T (mmHg), and M is the molecular weight of the chemical.

Trace organics in treated wastewater effluents consist primarily of low-molecular-weight, nonpolar organic substances whose high vapor pressure and relatively low solubility in water are especially conducive to rapid volatilization. At the concentrations at which they are present in the water, even a slight volatilization could be significant in solute transport. As the molecular weight of the organic substances increases, the saturated vapor pressure and the solubility frequently decrease to levels difficult to measure accurately. For a high-molecular-weight organic substance, it is essential that K_w be determined from actual experimental data [24].

Table 15-3 summarizes the K_w for selected trace organics of wastewater effluents calculated by equation 15-6. Except for phthalate esters, all other trace organic chemicals listed in Table 15-3 should be subject to rapid volatilization in soil solution.

In the soil, the mass transfer through volatilization depends not only on the partition of a chemical between the water and the air but also on movement of the chemical to the soil surface and its dispersion in the air. Consequently, the actual volatilization loss of trace organics from the soil will depend on factors affecting the movement of chemicals to the soil surface and of volatilized compounds away from the water/air interface [25].

The values of K_{oc} and K_w tabulated in Table 15-3 describe the relative importance of soil adsorption and volatilization among a group of selected trace organic substances. In order to assess the fate of a chemical in soil, it is essential to compare the properties of the substance in question with organic substances whose environmental behavior is well understood. By assuming that (1) the rate of leaching is proportional to the amount of the trace organic substance in the aqueous phase of the soil system and (2) the rate of volatilization is proportional to the amount of the trace organic substance in the atmospheric phase of the soil system, Laskowski et al. [11] derived the following mathematical expressions for leaching potential and volatilization potential of an organic substance:

$$\text{Leaching Potential} = S_{25}/(V_p \times K_{oc}) \qquad [15\text{-}7]$$

$$\text{Volatilization Potential} = V_p/(S_{25} \times K_{oc}) \qquad [15\text{-}8]$$

where S_{25} is water solubility of the substance at 25°C (ppm), and V_p is the saturated vapor pressure of the substance at 25°C. Table 15-4 summarizes the calculated leaching potential and volatilization potential of selected trace organic substances found in treated wastewater effluents. They are compared with the leaching and volatilization potentials of four pesticide residues (2,4-D, malathion, lindane and DDT) whose behavior in the soil has been studied extensively. It is obvious that trace organic substances in wastewater effluent have a leaching potential similar to DDT the soil. However, most trace organic substances are far more likely to volatilize from the soil than DDT.

Table 15-3. Soil adsorption constant (K_{oc}), water-air partitioning coefficient (K_w), and octanol-water partitioning coefficient (K_{ow}) of selected trace organic substances.[a]

Compounds	K_{oc}	K_w	K_{ow}
Chloroform	81	8.3	93
Bromodichloromethane	70	--	76
Dibromochloromethane	99	--	123
Bromoform	140	--	200
Carbon tetrachloride	246	1.0	437
Methyl chloride	129	--	178
1,1,1-Trichloroethane	113	0.7-6.4	148
Tetrachloroethylene	230	--	398
Chlorobenzene	343	6.9-9.2	692
1,2-Dichlorobenzene	839	12.2	2,399
1,3-Dichlorobenzene	838	6.8	2,398
1,4-Dichlorobenzene	853	7.5	2,455
1,2,4-Trichlorobenzene	3,607	7.3	18,197
Ethylbenzene	573	3.74	1,413
m-Xylene	622	--	1,585
p-Xylene	573	--	1,413
Napthalene	825	--	2,344
Dimethyl phthalate	104	47,076	132
Diethyl phthalate	643	--	1,660
Di-n-butyl phthalate	17,140	--	158,489
Bis-[2-ethyl hexyl]phthalate	20,230	--	199,526
PCB (Aroclor 1242)	32,181	40.5	380,189
Lindane	1,474	1,047	5,248

a. K_{ow} values were from Callahan et al. [18,19]; K_{oc} and K_w of each compound are calculated by Equation 15-4 and Equation 15-6, respectively.

Table 15-4. Relative risk of trace organic substances leaching through the soil and volatilizing from the soil as compared with selected pesticide residues in soil.

Compounds	Volatilization potential[a]	Leaching potential[a]
Chloroform	2.3×10^{-4}	1.9×10^{-1}
Carbon tetrachloride	4.8×10^{-4}	1.3×10^{-2}
Methyl chloride	1.8×10^{-4}	4.0×10^{-1}
1,1,1-Trichloroethane	1.7×10^{-3}-1.9×10^{-4}	4.5×10^{-2}-4.2×10^{-1}
Chlorobenzene	1.5×10^{-4}	1.5×10^{-1}
1,3-Dichlorobenzene	1.2×10^{-5}	1.2×10^{-1}
1,3-Dichlorobenzene	2.2×10^{-5}	6.5×10^{-2}
1,4-Dichlorobenzene	1.7×10^{-5}	7.8×10^{-2}
1,2,4-Trichlorobenzene	3.8×10^{-6}	1.9×10^{-2}
Ethylbenzene	8.0×10^{-5}	3.9×10^{-1}
Dimethyl phthalate	1.9×10^{-8}	34.6
2,4-D	1.1×10^{-11}	2.5×10^{7}
Malathion	2.9×10^{-10}	4.0×10^{3}
Lindane	1.6×10^{-7}	3.6
DDT	4.7×10^{-10}	3.7×10^{-2}

a. Leaching potential and volatilization potential of each substance are calculated according to Equations 15-7 and 15-8. Compounds with higher values are more likely to volatilize or be leached in the soil.

Biodegradation

In the soil, trace organic substances may be removed from the applied wastewater effluent by adsorption or volatilization, wherein the chemical structure of the compounds are not altered in the processes. There are experimental data that demonstrate the rapid desorption of the adsorbed trace organics when the soil is leached with a trace-organics-free water [15]. This reversal of the adsorption process releases the potentially hazardous chemicals to the aqueous phase.

Biodegradation is an enzyme-activated biochemical reaction whereby organic substances are effectively decomposed. Bacteria, actinomycetes, and fungi are the soil micro organisms most important in the decomposition of organic substances in the soil. Although the biochemical pathway responsible for breaking down trace organic substances is not entirely known, the microbial metabolisms are well understood. Biochemical reactions such as β-oxidation, cleavage of ether linkage, ring hydroxylation, ring cleavage, ester hydrolysis, dehalogenation, and n-dealkylation are all common to the degradation of pesticide residues in the soil [26]. However, enzymes responsible for the reactions may have to be induced. The same biochemical mechanisms are applicable to the degradation of trace organic substances introduced into the soil by wastewater irrigation. Biodegradation thus offers the means to detoxify trace organics retained by the soil.

The rate of biodegradation in soils is influenced by the type of microorganism, the characteristics of the soil, and the molecular structure of the compound [27]. The degradation processes of poorly adsorbed water-soluble trace organics may be described by the Michaelis-Menten reaction kinetics. At high substrate concentrations (>2.5 μg/mL), the rate of degradation appears to be independent of the substrate concentration (zero-order reaction). At low substrate concentrations, the decomposition becomes a first-order reaction. However, it is essential that reaction kinetics and breakdown in the soil be properly defined.

Following an extensive review of the literature, Callahan et al. [19] concluded that the biodegradation pathway of organic priority pollutants may be developed on a theoretical basis or extrapolated from experiments of compounds with similar chemical structures. Few experimental data are available to confirm the speculation. Tabak et al. [28] studied the biodegradability of 96 organic priority pollutants using the static-culture flask screening procedure developed by Bunch and Chambers [29] at 5 mg/L and 10 mg/L substrate concentrations. Their results are summarized in Table 15-5. Except for chlorodibromomethane and heptachlor, organic priority pollutants found in the influents from publicly owned treatment works (Table 15-1) can be biologically degraded. At the concentrations in which they are present in the wastewater effluent, it is questionable whether a viable microbial population will be maintained with trace organic substances as the sole carbon source. Reaction rates are expected to be considerably lower at low substrate concentrations [30]. Experimental results have demonstrated that significantly higher levels of trace organic reductions may be achieved when they are used as the secondary substrate. Therefore, the presence of readily available organic carbon sources in the soil would undoubtedly enhance the degradation of trace organics. Because adsorbed trace organics generally will not be subject to microbial attack, the rate of biodegradation for trace organics in the soil may also be slowed by adsorption.

Bioaccumulation

In this discussion, the possibility of trace organic substances being absorbed by crops has not been raised. Examples from the study of pesticide residues and polynuclear aromatic hydrocarbons in the soil show that some degree of plant absorption of trace organic substances will occur (magnitude lower than that of pesticides) [31]. Since there are no known physiological pathways for plants to absorb trace organics, the most likley mechanism would be by mass flow. Once the trace organics are adsorbed by the soil, the amounts available for plant uptake become limited. Because of their hydrophobic nature, trace organic compounds of high K_{ow} are expected, upon entering the plants, to be deposited primarily in the plant roots [32,33]. The lower-molecular-weight trace organic compounds that are gradually assimilated by plant tissue should not exhibit symptoms of

Table 15-5. Summary of biodegradability of organic priority pollutants derived from data in Tabak et al. [28].

Tested Compounds[b]	Biodegradability[a]					
	Significantly Degraded	Significantly Degraded After Acclimation	Slowly to Moderately Degraded	Very Slowly Degraded	Significant Degradation With Subsequent Toxicity	Not Significantly Degraded
Phenolic compounds	Phenol 2-Chlorophenol 2,4 Dichlorophenol 2,4-6 Trichlorophenol 2,4-Dimethylphenol P-Chloro-m-cresol 2-Nitrophenol 4-Nitrophenol 2,4 Dinitrophenol	Pentachlorophenol				4,6-Dinitro-o-phenol
Phthalate esters	Dimethylphthalate Diethylphthalate Butylbenzylphthalate	Bis-(2-ethyl hexyl)phthalate Di-n-octylphthalate				
Naphthalenes	Nathalene 2-Chloronaphalene Acenapthene Acenaphthylene					
Monocyclic aromatic hydrocarbons	Benzene Chlorobenzene[c] Nitrobenzene Ethylbenzene Toluene	Chlorobenzene[c] Ethylbenzene[c]			1,2-Dichlorobenzene 1,3-Dichlorobenzene 1,4-Dichlorobenzene 1,2,4-Trichlorobenzene 2,4-Dinitrolene 2,6-Dinitrolene	Hexachlorobenzene
Polycyclic aromatic hydrocarbons	Phenanthrene Pyrene[d]	Anthracene Fluorene Fluoranthene[d] Chrysene[d]				Fluoranthene[d] Chrysene[d] Pyrene[d] 1,2-Benzanthrancene
Halogenated ethers	Bis-(2-Chloroethyl)ether 2-Chloroethyl vinylether Bis-(2-Chloroisopropyl)ether					4-Chlorodiphenylether 4-Bromophenylether Bis-(2-Chloroethoxy)ether
Polychlorinated byphenyls	PCB-1221 PCB-1232					PCB-1016 PCB-1242 PCB-1248 PCB-1254 PCB-1260
Nitrogenous organics	N-Nitrosodiphenylamine[c] Isophorone Acrylonitrile Acrolein				1,2-Diphenylhydrazine	N-Nitroso-di-N-propylamine
Halogenated aliphatic hydrocarbons	Hexachloroethane Methylene chloride Bromochloromethane Carbon tetrachloride Hexachloro-1,3-butadiene Hexachloro-cyclopentadiene	1,1-Dichloroethane Chloroform Dichlorobromomethane Bromoform 1,1-Dichloroethylene Trichloroethylene Tetrachloroethylene 1,2-Dichloropropane 1,3-Dichloropropylene	1,2-Dichloroethane 1,1,1-Trichloroethane 1,2-Dichloroethylene-cis 1,2-Dichloroethylene-trans	1,1,2-trichloroethane		Chlorodibromomethane Trichlorofluoromethane
Organichlorine pesticides						Aldrinane Dieldrine Chlordane DDT DDE DDD α-Endosulfan β-Endosulfan Endosulfan sulfate Endrin Heptachlor Heptachlorepoxide Hexachlorocyclohexane

[a] Biodegradability of organic priority pollutants were tested by batch culture procedure with microbial inoculum from a settled sewage at 25°C for 7 days. Significantly degraded: substrate concentration less than 0.1 ml/l at the end of the testing period. Significantly degraded after acclimation: significant degradation after 1-3 weeks of microbial adaptation. Significantly degraded with subsequent toxicity: degradation exhibited initially was lost due to loss of the metabolically efficient microbial population or gradual buildup of toxicity. Slowly to moderately degraded: total loss of the substrate compounds in 7 days incubation time less than 95% with significant amounts caused by volatilization. Very slowly degradable: substrate degradation less than 50% even with long microbial adaptation period. Not significantly degraded: substrates are not significantly degraded under the test conditions and/or precluded by extensive rate of volatilization.

[b] Priority pollutant compounds not texted are Benzo(a)-pyrene, 2,4-Benzofluoranthene, Benzo(k)-fluoranthene, Benzo(g,h)perylene, Dibenzo(a,h)anthracene, Indeno(1,2,3-cd)pyrene, Toxaphene, Dioxin, Endrin aldehyde, Benzidine, 3,3'-Dichlorobenzidine, Bis-(2-chlorometyl)ether, N-nitrosodimethylamine, Vinyl chloride, Chloroethane, Methylchloride, Methylbromide, and Dichlorodifluoromethane.

[c] Compounds significantly degraded at low substrate concentration (5 mg/l) and required microbial adaptation before significant degradation took place at a high substrate concentration.

[d] Biological degradation of the compound was not observed at high substrate concentration (10 mg/l).

bioaccumulation. Unless there are data to indicate otherwise, accumulation of trace organics in the plant tissue through root absorption is not expected to be significant.

CONCLUSION

Trace organic substances are a group of newly discovered contaminants of water supplies. Since their discovery, several hundred potentially hazardous organic chemicals have been found in natural water, wastewater, and drinking water. Because of the inherent toxic effects associated with many trace organic substances, their presence in the water (even at low concentrations) has caused great concern.

Although conventional wastewater treatment processes are not designed for trace-organic removal, such processes can greatly reduce the number and concentrations of trace organics. For this reason, the environmental risk associated with using the treated wastewater for irrigation should not be greater than that associated with using other sources of water, which may also contain trace organics.

When trace organics are introduced into the soil through wastewater irrigation, the most effective mechanisms of attenuation are expected to be adsorption, volatilization, and biodegradation. Because there are few data to quantitatively describe the fate of trace organics in soil, the soil adsorption coefficient (K_{oc}), water-air partition coefficient (K_w), and octanol-water partition coefficient (K_{ow}) of selected trace organics of the treated wastewater effluent provide useful indexes of the behavior of trace organics. When they are compared with several pesticides whose environmental fate and transport in the soil are well defined, it becomes obvious that most trace organics of the wastewater will be attenuated in the soil in a manner similar to attenuation of pesticide residues. Because the inputs of trace organic matter through irrigation are usually smaller than the application of pesticides, the environmental impact associated with their presence in wastewater effluents is not expected to be very significant.

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APPENDIX A

SELECTED MUNICIPAL WASTEWATER IRRIGATION PROJECTS IN CALIFORNIA

INTRODUCTION

This appendix contains descriptions of 17 municipal wastewater irrigation projects in California (Figure A-1). These descriptions were prepared by Boyle Engineering Corporation in March 1983. An earlier version of these descriptions was published in 1981 [1].

BAKERSFIELD

Bakersfield, located at the southern end of the San Joaquin Valley, has used wastewater to irrigate croplands for more than 60 years.

The treatment plant effluent is used to irrigate approximately 5,100 acres that the city owns and leases to a farmer. The city's lease with the farmer is quite specific about his responsibilities. He is required to take all of the wastewater produced by the treatment plant and use it for irrigation on those crops that meet State Health Department and California Regional Water Quality Control Board (CRWQCB) requirements. The annual cost to the lessee for the leased land and water is $80 per acre. The lease is for 14 years beginning in 1979.

The city owns a total of 5,770 acres. More than half of this land was recently purchased from the railroad, and it was poor agricultural ground with soils high in salinity and alkalinity.

The city has completed a land reclamation program including leveling, ripping, and applying gypsum at a rate of 10 tons/acre. Indications are that the land reclamation program is successful. The project is designed to provide waste treatment using the reclaimed water to irrigate the city-owned acreage through 1996. By that time, approximately 54 inches of reclaimed water per year will be applied to the 5,100 acres.

Many agricultural crops are grown in the Bakersfield area, including orchard, row, and field crops. Crops grown in the area

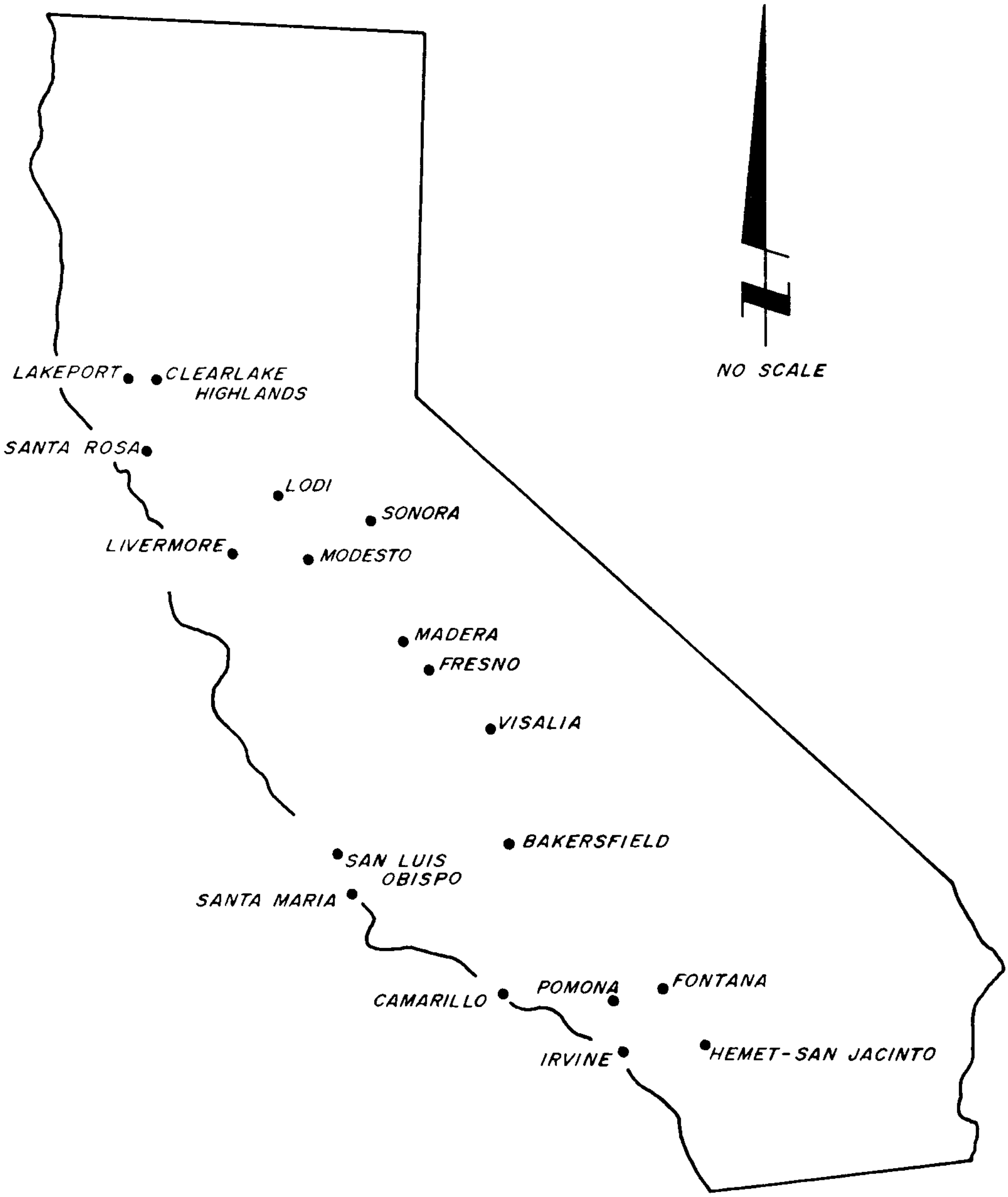

Figure A-1. Reviewed reclamation projects.

surrounding the city farm are cotton, corn, barley, alfalfa, sorghum, wheat, and permanent pasture. The city's tenant is growing barley, corn, cotton, alfalfa, sorghum, and permanent pasture.

The soils in the area consist of Bishop clay loams, Cajon fine sandy loams, Foster fine sandy loams, Hesperia-Cajon complex, and Traver fine sandy loams. All of these soils are affected by salt and alkali in their virgin state. The soils generally are extremely saline and alkali and in some areas contain high boron. Drainage and permeability of soils vary: the Cajon and Foster series have fairly good drainage, the Traver has fair drainage, the Hesperia-Cajon complex has fair to poor, and the Bishop series has poor drainage. Groundwater in the area varies from 4 ft to more than 15 ft in depth from the surface.

Before soil reclamation was initiated, many parcels had soil electrical conductivities of more than 16 mmho/cm with the exchangeable sodium percentage exceeding 60%. The soil reclamation program implemented in 1977-78 consisted of ripping to a depth of 30 inches, followed by land leveling to permit flood or furrow irrigation. Then after the ground was disked smooth and temporary irrigation borders were made, the field was irrigated. Ten tons of 60% gypsum were then disked and cross-disked into the top 6 inches of soil. Barley was planted in the fall of the first year and was irrigated during the winter and early spring to keep the crop growing. In those areas with poor growth, another 10 tons/acre of 60% gypsum were applied, and in the summer the areas were planted to a crop of Sudan grass or grain sorghum using border strip irrigation. After this crop was harvested, soil was analyzed to determine whether additional gypsum should be applied. In the late summer, the field was planted in pasture or alfalfa and border-irrigated, and the soil conditions were monitored until salinity levels reached a safe level at which furrow irrigation could be used.

The estimated amount of nitrogen (N) in the water is about 60 lbs/acre-ft. This amount will satisfy the nitrogen fertilizer requirements of most crops. Past tenants had problems growing cotton: vegetation was excessive, and the cotton bolls did not set. This is probably due to the presence of nitrogen in the water during the

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latter part of the growing season. To correct this problem, the present tenant uses reclaimed water in the early part of the season and switches to well or canal water in the latter part of the season.

CAMARILLO

Camarillo is located approximately 50 miles northwest of Los Angeles. The treatment plant has secondary treatment consisting of activated sludge, followed by chlorination and dechlorination. When irrigation water is not required, the Sanitation District has a NPDES permit to discharge into Conejo Creek adjacent to the treatment plant. Because of the permitted creek discharge, there are no restrictions on the discharge of irrigation tailwater into Conejo Creek. The treatment plant has recently been expanded from a capacity of 4.75 mgd to 6 mgd.

Since construction of the treatment plant in the late 1950s, approximately 400 acres of land adjacent to the treatment plant have been irrigated with reclaimed water. This land is now leased by a farmer who has been farming the land for 18 years. He receives the reclaimed water as part of his lease with the owner and uses the water at his own risk.

Agricultural commodities grown in the Camarillo area include strawberries, broccoli, cauliflower, tomatoes, various other truck crops, citrus, avocados, and turf sod. The farmer leasing the land adjacent to the plant is using reclaimed wastewater to furrow-irrigate beans, chili peppers, tomatoes, and broccoli. Alternative irrigation water sources include surface water from the California Water Project, with an agricultural water cost of about $122/acre-ft, or well water, with an average cost of $56/acre-ft. The cost of the reclaimed water is incorporated into the lease.

The use of reclaimed water appears to be well accepted in the farming community around Camarillo. The farmer leasing the land next to the plant indicates that production is equal to or higher than that in other areas he farms within the Oxnard Plain using fresh water. Flies, odor, and other vector problems were not detected on or around the 400-acre farming site, and no health problems related to the use of reclaimed water at this location have been reported.

FONTANA

The Fontana Wastewater Reclamation Plant is located in the City of Fontana at the north end of the Chino Basin and is operated by the Chino Basin Municipal Water District. The plant provides only primary treatment for an average daily flow of 3 mgd. Since construction of the plant in the 1950's, a portion of the reclaimed water has been used to irrigate adjacent orchards and vineyards. The primary method of ultimate disposal has been via percolation ponds at the plant site. The ponds serve both as disposal through evaporation and percolation and as storage for agricultural irrigation. The plant is operated under an order issued by the CRWQCB, Santa Ana Region. The operator states that the treatment facility operates with a high level of dependability and reliability.

FRESNO

The Fresno Wastewater Treatment Facilities consist of two separate plants with a combined average daily flow of 43 mgd. Both plant treatment processes include prechlorination for odor control as well as preliminary, primary, and secondary treatment. Plant #1 is the larger facility and utilizes activated sludge for its secondary treatment. Plant #2 utilizes trickling filters for its secondary treatment. Although Plant #2 effluent may go directly to the percolation ponds, better overall effluent quality is obtained by diverting it through the aeration basins for additional secondary treatment.

The city has a separate industrial waste sewer and disposal facility to handle winery stillage wastes, which would upset biological treatment of the domestic sewage.

The municipality owns 2,000 acres at the treatment plant site, of which 1,500 acres are divided into 93 separate percolation beds. If necessary, all of the wastewater from the treatment facility can be disposed of in the percolation beds. At present, about 600 acres of the percolation beds are leased to a farmer who is producing cotton and silage corn within the beds. Pipes and open channels provide reclaimed water to neighboring farmers along the perimeter of the 1,500 acres. In 1979, approximately 2,960 acres of private land adjacent to the treatment facility were irrigated with reclaimed water, and approximately 600 acres were farmed within the percolation beds.

Strategically spaced throughout the infiltration beds are 21 separate extraction wells, each with a capacity of up to 1,200 gpm. The extraction wells are approximately 250 to 300 ft deep and pump into a common pipeline, which discharges either into Dry Creek Canal, which passes through the 1,500-acre site, or into the Houghton Canal. Both canals serve as part of the Fresno Irrigation District's agricultural water supply system. By percolating the reclaimed water through the soil profile and extracting it with these reclamation wells, a form of tertiary treatment is accomplished at a very low cost.

The treatment facility is operated under a waste discharge permit from the CRWQCB, Central Valley Region. The six farmers using reclaimed water have reclamation permits from the CRWQCB that require them to report on a monthly basis the quantity of reclaimed water used and the crops irrigated with it. Each farmer has a written agreement with the city that requires them to use the reclaimed water in accordance with state regulations.

Numerous crops are grown in the surrounding area. Those crops grown and irrigated with reclaimed water include cotton, barley, alfalfa, grapes, silage corn, oats, wheat, and sorghum. The reclaimed water is available to the adjacent farmers at several points along the perimeter of the treatment facility and is supplied free of charge. The farmers must provide their own transmission and distribution system from the perimeter of the treatment facility. Reclaimed water has been used for more than 30 years to irrigate crops in the area. Through September of the 1979 irrigation season, more than 7,000 acre-ft of reclaimed water were used for crop irrigation within the percolation beds and the surrounding private land. Within the same period, more than 18,000 acre-ft were extracted from the 21 reclamation wells and exported to the Fresno Irrigation District.

The soils in the area around the reclamation facility are typically sandy loam. The farmer leasing the 600 acres within the percolation beds has observed infiltration problems that are probably related to the water and soil chemistry. He indicated that the percolation ponds being farmed have consistently had water ponded in them, are extremely sandy, and do not have the water soaking or retention capability that they originally did. This farmer and two others indicated that they apply little or no chemical fertilizers to their crops because of the nitrogen contained in the reclaimed water. Also, they feel the water is of high quality, thus requiring little leaching for salt control.

They have not experienced health problems associated with the reclaimed water, nor have they noticed health problems with their employees.

HEMET-SAN JACINTO WATER RECLAMATION FACILITY

The Hemet-San Jacinto Valley is located in Riverside County southwest of Mount San Jacinto. The Eastern Municipal Water District operates and maintains the Hemet-San Jacinto Water Reclamation Facility. The treatment plant is being expanded from 5.0 to 7.5 mgd and is currently operating at 5 mgd. Treatment consists of primary and secondary treatment (conventional activated sludge type). The solids removed in the process are treated by anaerobic digestion, and the secondary effluent can be disinfected through the use of "on site" chlorination.

The District has seven existing agreements with reclaimed water users for the total amount of water produced by the treatment plant. Two of the users are duck clubs, which require the reclaimed water to be chlorinated in order to meet State Health and Regional Water Quality Board requirements during the duck-hunting season (October 15 through January 15). The agreements with the users commonly provide for a minimum of 5 lbs/in^2 discharge pressure at the individual meters. The District has approximately 522 acre-ft of storage capacity that can be used during wet weather periods. The users purchase reclaimed water at the present (1983) rate of approximately \$13.00/acre-ft. The water cost for the duck clubs during those periods requiring chlorinated water is approximately \$30.00/acre-ft. This price is adjusted annually as necessary, to account for operational labor, energy, and related expenses.

IRVINE

The Irvine Ranch Water District (IRWD) is located in southern Orange County, which at one time was a large agricultural area but is now rapidly being urbanized. The water district operates the Michelson Water Reclamation Plant, which provides primary, secondary, and advanced treatment. The secondary treatment process is activated sludge, followed by dual media sand filtration and extended chlorination. The plant is operating at an average daily flow of approximately 8.2 mgd and has a design capacity of 15 mgd.

The IRWD has an extensive irrigation water distribution system, and its primary source of water is reclaimed water from the Michigan Water Reclamation Plant. The irrigation system supplies water for both landscape and agricultural irrigation. The principal agricultural irrigation water user is The Irvine Company, which has irrigated with reclaimed water since the mid 1960's and annually uses more than 6,000 acre-ft on various fruit trees and row crops. The Irvine Company uses the reclaimed water under a reclamation permit issued by the CRWQCB, Santa Ana Region, that requires them to submit monthly reports identifying the method of irrigation, crops, and quantity of water used. The district owns and operates two storage facilities: Rattlesnake Reservoir, with an available capacity of 1100 acre-ft, and Sand Canyon Reservoir, with an available capacity of 450 acre-ft. These are storage facilities principally for reclaimed water. Reclaimed water is distributed directly from the plant or impounded within the reservoirs, refiltered, and distributed as necessary. The water leaving the reservoirs for landscape use must be filtered to remove particulate matter and aquatic plant growth that occurs in the reservoirs. This is necessary to prevent plugging of the various components within the landscape irrigation system. The irrigation water is sold according to a district rate schedule.

Storage of reclaimed water during the winter months is one of the district's major reclamation problems. This has been an especially difficult problem during 1978-1980 because of the large amount of rainfall received in Orange County and the low irrigation demands during the winter months. Seasonal storage of the reclaimed water is required, as is storage of the surface runoff that also flows into the reservoirs. The district is not permitted to discharge into local drainage water courses. However, for the winter of 1979-1980, the district was granted an emergency discharge permit that allowed them to discharge from the reservoir into San Diego Creek when the reservoirs were full and had the potential of discharging over their spillways.

There are no formal contracts between the farmers and the district governing the use of reclaimed water. Generally, the CRWQCB issues reclamation permits individually to the users.

Reclaimed water quality from the IRWD is typical of that of other reclamation projects in Southern California. The water is high in total dissolved salts (800 to 1,000 mg/L) and boron (0.4 to 0.8 mg/L). There was one case in 1975 when sprinkler-irrigated crops were damaged by an excess amount of residual chlorine at a level of approximately 100 mg/L in the reclaimed water. The IRWD voluntarily reimbursed the farmer for the damage.

The Irvine Company is very concerned about the high concentrations of boron and other components in the reclaimed water and its effect on the citrus and other boron-sensitive crops. Since the early 1970's, soil samples from the various orchards and fields where reclaimed water is used have been taken to determine whether concentrations of these components are approaching toxic levels. Samples are taken at the beginning and at the end of the irrigation season to detect any buildup of toxic material during the season. It has been observed that TDS, boron, and other materials do tend to concentrate in the root zone during the irrigation season, and the normal rainfall during the winter months appears to leach them through the root zone. Over the last 10 years, boron levels in the reclaimed water have been as high as 1.25 mg/L, with no observed toxic effect on the citrus; an average level is about 0.06 mg/L. Crop nutrition programs at The Irvine Company are based on plant tissue analysis; fertilizers are used to supply those nutrients not present in the soil and reclaimed water in adequate amounts.

Exposed water conveyance facilities such as standpipes are marked with a notice that they contain reclaimed water. Reclaimed water usage is in accordance with DOHS guidelines and is monitored by the

CRWQCB. When the reclamation program was in its infancy during the late 1960's and early 1970's, there were problems with solids in the water that were plugging sprinklers and even gated pipe. These problems have been solved, and reclaimed water is a dependable irrigation water source in the Irvine area.

LAKE COUNTY

The Clear Lake area is located approximately 100 miles northeast of San Francisco in Lake County. Two reclamation projects are operated by the Lake County Sanitation District, one located north of Lakeport at the north end of Clear Lake, and the other at Clearlake Highlands near the south end of Clear Lake.

Treatment Plant No. 3, located near Lakeport, was recently constructed and put into operation. It has a design capacity of 2.1 mgd, with an average dry-weather flow of 0.7 mgd and wet-weather flow of 1.7 mgd. Wet-weather flows are high because of extensive groundwater infiltration inflow into the sewers during winter. The plant has secondary treatment followed by chlorination. An extended aeration racetrack provides secondary treatment. The effluent is used to irrigate permanent pasture located adjacent to the plant and owned by the sanitation district. The district owns approximately 1000 acres, of which 240 acres is irrigated pasture and 300 acres is dry farm pasture; the latter will be available for irrigation in the future as plant production increases. Irrigation is by solid-set sprinklers with wide spacing. The district also maintains an 800 acre-ft reservoir used to contain treatment plant flows during the winter.

The district operates under a reclamation permit issued by the CRWQCB that prohibits runoff from the irrigation site during the irrigation season. At the low end of the irrigated area, a recapture reservoir collects irrigation runoff for recycling into the irrigation system or for storage in the large reservoir. The reclamation permit requires the district to catch the runoff from the first winter storm and return it to the large storage reservoir. After the first winter storm, runoff can be discharged through the recapture reservoir and into Clear Lake. The only water-quality requirement specified in the reclamation permit is that suspended solids be 40 mg/L or less and biochemical oxygen demand (BOD) be 30 mg/L or less.

The Lake County Sanitation District Plant No. 1 at Clearlake Highlands is identical to Plant No. 3 in treatment processes and general operation. In the latter part of 1979, the plant had a capacity of 1.75 mgd, with a dry-weather flow of 0.6 mgd and a wet-weather flow of 1.3 mgd. The plant has a 240 acre-ft storage reservoir, which will be expanded to 470 acre-ft over the next few years. There are 280 acres of irrigated permanent pasture. The recapture reservoir and plant are operated the same as those in Plant No. 3.

The sprinkler system at reclamation Plant No. 3 near Lakeport consists of aluminum surface pipe and risers. The system at Clearlake Highlands consists of a totally buried main and submain system, using both PVC and asbestos-cement pipe with heavy galvanized iron risers. This system has been in service since 1975. The sprinkler spacing at both operations does not provide for any overlap. This maximizes the amount of area for reclaimed water disposal with a minimum amount of irrigation equipment. Each irrigation system has a full-time operator responsible for both the operation and maintenance of the system.

Irrigation systems at both reclamation projects are relatively new. They are located in very rural areas and have not presented nuisance problems to the surrounding communities. The Air Pollution Control Board has expressed some concern over bacteria in spray drift from the facilities but has taken no action.

LIVERMORE

The city of Livermore is located in Alameda County approximately 20 miles east of Oakland and 35 miles west of Stockton. The water reclamation plant is located adjacent to the Livermore Municipal Airport, South of Highway 580.

Approximately 150 acres of city-owned land are irrigated with reclaimed water from the reclamation plant. Water is distributed to this land by buried pipelines. The method of irrigation is fixed sprinkler. Approximately 15% to 20% of the treated wastewater is reclaimed for irrigation. The remainder is discharged into

San Francisco Bay through facilities completed in 1980. Excess water is transported from the plant through a buried pipeline owned by the Livermore-Amador Valley Water Management Agency to facilities located near the treatment plant at Dublin-San Ramon. At this point, it is pumped over a hill through facilities owned by the East Bay Discharge Authority and discharged into the bay.

Treatment processes used at the plant include primary sedimentation, activated sludge, coagulation, direct filtration, and chlorination. Plant capacity is 6.25 mgd. Average daily dry-weather flow is 4.4 mgd, and maximum daily flow may be as high as 5.0 mgd. The plant has an average of two shutdowns per year due to system failure. When this occurs, wastewater influent is stored in a lined reservoir until the plant is repaired.

The farmed acreage in the Livermore area has been reduced rapidly because of urban encroachment. Reclaimed water is used for irrigation of an 18-hole golf course and will be used soon for landscape irrigation along the Highway 580 right-of-way. Nearby agricultural lands that have been irrigated with reclaimed water have been sold for light industrial use. The use of reclaimed water for landscape irrigation on these lands, once they are developed, is being considered.

LODI

The city of Lodi is located in the delta area of central California between Stockton and Sacramento. The sewage treatment facility is about 5 miles west of the city. Both industrial and domestic wastes were treated at the plant, but in 1981 direct irrigation with cannery wastewater began. Domestic waste is treated, chlorinated and dechlorinated, and discharged into White Slough, which eventually discharges into San Francisco Bay. Industrial waste influent is discharged directly into an aeration pond without being treated in the plant. After aeration, it is pumped into a settling pond and then into one of two storage reservoirs. Detention time in the reservoirs ranges from 20 to 30 days, depending on the time of year. The industrial effluent is used for irrigation of agricultural crops; domestic effluent supplements it in the summertime. In general, during the summer all of the water is used for irrigation, but in the winter only the industrial effluent is reclaimed and the domestic effluent is discharged into the slough. The maximum discharge time into White Slough is approximately 150 days/yr.

Industrial effluent is not chlorinated when it is discharged into the storage reservoirs and used for irrigation. It consists of wastewater from several canneries in the area, a chrome-plating operation, and other minor industrial contributors. Water is distributed from the two storage reservoirs in concrete-lined canals, but field ditches are generally unlined. All of the irrigation tailwater is collected in unlined tailwater ditches. This tailwater drains into a buried pipeline through a surface grate. It is then recirculated either into an equalization pond or to the storage reservoir.

Treatment processes used at the plant include primary sedimentation, activated sludge, chlorination for domestic influent, and oxidation and settling ponds for industrial influent. The plant design capacity is 9.6 mgd but is operated with an average dry-weather flow of 7 mgd and a maximum daily flow as high as 12 mgd. Plant reliability has been excellent, and shutdowns due to system failure or other problems have generally been nonexistent. However, if problems occur, holding ponds are available to retain influent flows during repair operations.

Reclaimed water is used at the site to irrigate pasture, alfalfa, and a small test plot of eucalyptus trees.

An area farmer said that he gets better growth early and late in the season because of the warm temperature of the reclaimed water. He also feels that his pasture is as good as any in the area, even though he does not apply fertilizer.

The chrome-plating operation could be a source of toxic concentrations of chromium and zinc. Water-quality data are not available to support this hypothesis, and problems with crop or animal toxicity attributable to heavy metals have not been reported. There is no evidence to indicate degradation of soil or groundwater quality due to irrigation with reclaimed water. However, odor problems have occurred during the summer when the plant is receiving cannery wastewater.

MADERA

The city of Madera is located in the central San Joaquin Valley 20 miles north of Fresno. The sewage treatment plant is 50 miles west of the city.

The city of Madera owns approximately 320 acres of farmland that is leased to a grower and irrigated with reclaimed water. The reclaimed water may in some instances be supplemented with well or ditch water. The farming site consists of twelve 20-acre ponds and one 80-acre field. The ponds are used for water storage, percolation, and balancing irrigation water flows. In general, 4-6 ponds are used for storage each year; however, under conditions of abnormally high winter precipitation, more ponds may be required. All of the crops at the site are flood- or furrow-irrigated. Sludge is generally pumped to an adjacent field and incorporated by disking or plowing. In some instances, sludge may be mixed with reclaimed water before irrigation. No reclaimed water or sludge leaves the site.

Treatment processes used at the plant include primary sedimentation and trickling filters. The reclaimed water is not chlorinated before irrigation. The treatment plant design capacity is 7 mgd with an average annual flow of 3 mgd. Generally, the treatment plant's reliability has been excellent.

The crops currently grown with reclaimed water at the site include cereal grains, cotton, and Sudan grass.

MODESTO

The city of Modesto is located about 30 miles south of Stockton in the San Joaquin Valley. The sewage treatment plant is in the southwest portion of the city.

Primary treated effluent is pumped from the treatment plant through a 60-inch buried transmission pipeline for approximately 8 to 10 miles to an aeration storage basin. The aeration basin covers about 843 acres and has a storage capacity of about 1.3 billion gallons (3,990 acre-ft). Water is circulated through the basin at a rate of about 220 mgd. From this facility, water can be chlorinated and discharged into the San Joaquin River or pumped into transmission facilities for irrigation of adjacent lands. The water can be chlorinated before irrigation use, but this is generally not done. Approximately 775 acres of adjacent land are irrigated with reclaimed water. Although the grower receiving this water has a contract to take as much as 9,500 acre-ft per year, annual reclaimed water use is generally much less than this.

Reclaimed water is applied to irrigated permanent pasture, alfalfa, and forage crops, such as silage oats and silage corn. These crops are used to feed replacement heifers.

Treatment processes include primary sedimentation, oxidation ponds, and chlorination. The plant capacity is 60 mgd. Average daily dry-weather flow is approximately 44.7 mgd (August and September 1982), and maximum daily flow may be as high as 51.6 mgd. The city of Modesto anticipates that starting in 1986, excess reclaimed water that is not utilized on land adjacent to the storage facility will be pumped into irrigation district facilities west of the site. This will virtually eliminate discharges into the San Joaquin River with the exception of periodic winter releases. Treatment plant reliability has been excellent. Storage basins are available at the primary plant site in case of plant shutdown. BOD and total suspended solids are monitored daily for both effluent discharges into the San Joaquin River and reclaimed water used for irrigation.

The farmer has not encountered problems using reclaimed water. The grower does not rely on the nutrient content of the reclaimed water to meet crop requirements: he applies sufficient fertilizer to satisfy crop requirements. Water quality can vary during the season as a result of discharges from canneries. During periods of cannery discharge, solids and BOD loadings increase.

POMONA

The city of Pomona is located on the east side of Los Angeles County. The Pomona Water Reclamation Plant is owned and operated by the Los Angeles County Sanitation District. The City of Pomona has an exclusive contract with the District for the purchase and marketing of reclaimed water within their service area. The city distributes the water for both agricultural and landscape irrigation, and the major agricultural user is the California State Polytechnic University. At present, the city sells approximately 5,100 acre-ft of reclaimed water to nine users on an interruptible basis.

Chlorinated irrigation water is being supplied by the District, which helps prevent growth of bacterial slimes and algae within the transmission and distribution system. The average flow during 1982 was 9.26 mgd.

Nearby California State Polytechnic University has expanded its utilization of reclaimed water to approximately 1,200 acre-ft/year, which is used to irrigate approximately 200 acres of agricultural land and 150 acres of ornamental shrubbery.

Reclaimed water is used to irrigate permanent pasture, alfalfa, various citrus and deciduous orchard crops, grapes, and some row crops, that require processing before being eaten. The irrigation methods are sprinkler, furrow, or drip irrigation, depending on the type of crop.

The majority of the reclaimed water users are irrigating landscapes such as parks and cemeteries. The City of Pomona has two industrial users of reclaimed water, both manufacturing paper products. Although the reclaimed water supply is reasonably reliable, all of the users have alternate water supplies.

The University has instituted a formal program to monitor the effects of reclaimed water on soils, and it is scheduled to be implemented in mid 1983. There is no formal program to monitor the effects on irrigated crops. Fields and orchards irrigated with reclaimed water have been observed to require less chemical fertilizer for good plant growth; however, on citrus, the reclaimed water does supply abundant amounts of nutrients at times when not required by the citrus crop.

SAN LUIS OBISPO

The city of San Luis Obispo is located about 10 miles inland from the Pacific Ocean. The biofiltration plant is located south of the city.

Reclaimed water from the treatment facility is discharged either into a pasture for direct irrigation or into a storage pond. Approximately 45 acres of permanent pasture at the site are flood-irrigated and used for grazing beef cattle and horses. Tailwater is collected at the lower end of the field and transported by an open, unlined surface ditch to the storage facility. Reclaimed water is not chlorinated before irrigation or storage in the pond. Tailwater and reclaimed water not used for irrigation is chlorinated and discharged into San Luis Obispo Creek. San Luis Obispo Creek discharges into San Luis Bay at Avila Beach. A substantial amount of acreage along San Luis Obispo Creek is irrigated with runoff water and reclaimed water that flows down the creek. In the summer, these areas are irrigated entirely with reclaimed water.

Wastewater treatment processes include primary sedimentation, trickling filters, oxidation ponds, and chlorination before discharge. The present plant capacity is 5 mgd. The average daily dry-weather flow is 3.5 mgd, and maximum daily flows may be as high as 7.0 mgd. Additional wastewater treatment facilities are now being constructed. New facilities will include advanced levels of treatment. When this system is installed and operating, excess reclaimed water will be discharged into Laguna Lake, a recreational facility. Reclaimed water will still be used for irrigating the 45 acres of pasture at the plant site, and additional minor landscape irrigation will take place adjacent to Laguna Lake. When the new facilities are operating, the water will no longer be discharged into San Luis Obispo Creek.

The plant is shut down twice a year, on an average, as a result of system failure. Problems that cause shutdowns may include power shortages, pump problems, and plugging. When these problems occur, ponds located at the treatment site are used for retention of sewage while the problem is resolved.

Reclaimed water is applied to pasture at the site and is also applied to pasture downstream from the biofiltration plant by pumping from San Luis Obispo Creek. At Avila Beach, just before being discharged into the Pacific Ocean at San Luis Bay, water is drawn from the creek and used for irrigating an 18-hole golf course.

The farmers in the area readily accept the use of reclaimed water primarily because of its price, availability, reliability, and nutrient content. The farmer managing the pasture at the plant site irrigated with reclaimed water believes the pasture is better in quality than the pasture in the surrounding agricultural area. This is attributed to the nutrient content of the reclaimed water. A San Luis Obispo County farm adviser said that the farmers who use reclaimed water are not applying commercial fertilizer. In his opinion, the pasture in the area where reclaimed water is applied is superior to other pasture areas in the county not irrigated with reclaimed water.

The grower that farms the 45 acres of pasture at the plant site pays essentially nothing for the reclaimed water, since the cost is included in the land lease. Growers downstream who withdraw water from San Luis Obispo Creek pay no water costs other than power for pumping. Irrigation water wells were not observed in the area downstream from the treatment facility; however, pumping installations were observed drawing water directly from San Luis Obispo Creek.

No health or disease problems, with either animals or workers, have been observed in areas where reclaimed water is applied. No odor problems have occurred at the site or downstream from it. The irrigated area at the treatment plant site is fenced and marked with signs; however, no signs were evident downstream where reclaimed water is applied to the pastures and golf course.

SANTA MARIA

The city of Santa Maria is located on the California coast about 10 miles inland from the Pacific Ocean and 30 miles south of San Luis Obispo. The wastewater treatment facility is located about 2 miles west of the city.

Secondary treated, unchlorinated wastewater from the sewage treatment plant is discharged into percolation ponds. The facility has about 40 acres of irrigated pasture and 60 acres of percolation ponds, which also serve to balance irrigation flows. Reclaimed water is applied by flood irrigation; irrigation sets are operated on about a 24-hour cycle.

The city owns about 40 acres of irrigated land. The 40 acres will be leased to a farmer to raise beef cattle. There are private individuals interested in leasing land around the plant for raising Christmas trees and using effluent for irrigation.

Treatment processes used at the plant include primary sedimentation and trickling filters. Plant capacity is 7.8 mgd. The average daily dry-weather flow is 4.2 mgd, and the maximum daily flow may be as high as 5.2 mgd.

Reduction of flow is the result of two large industries leaving the area. The plant superintendent indicated that plant shutdown due to power failure occurred on an average of less than once per year. No alternate pond storage facilities are available in case of plant breakdown; primary treated water is discharged into the treated percolation ponds. There is no method of crop protection in case of treatment plant breakdowns, and no alternate source of irrigation water is available. A private laboratory performs heavy metal analyses of the reclaimed water, and results are reported to the CRWQCB.

The cropping pattern in the area surrounding the treatment plant consists primarily of strawberries and vegetable crops grown for both fresh consumption and processing.

SANTA ROSA

The city of Santa Rosa is located in the center of Sonoma County, about 50 miles north of San Francisco. The city operates an extensive wastewater reclamation project that consists of two treatment plants and an irrigation system. The West College Treatment Plant has a designed capacity of 5 mgd and an average flow of 5 mgd. The plant provides secondary treatment plus chlorination. The recently completed Laguna Wastewater Reclamation Plant is located approximately 5 miles south of the College Park plant, has a design capacity of 15 mgd, and is currently operating with an average flow of 9 mgd. The Laguna plant provides activated sludge, secondary treatment, and chlorination. The city operates a reclaimed water irrigation system and has a pipeline connecting the two treatment plants.

There are 21 individual farmers using the reclaimed wastewater to irrigate approximately 3,400 acres of land. Water is distributed from the treatment plants into storage reservoirs, which can contain at least 60 days worth of treatment plant flow. From the storage reservoirs, the city operates an extensive pressurized irrigation distribution system, which includes storage or peaking reservoirs. The system is operated and maintained by the city, and the farmers take water on demand from the system.

The city's operating permit requires the farmers to dispose of the reclaimed water on land from May 15 to September 30. After September 30, the city can discharge into the Russian River if the flow is above 1000 ft^3/sec, and it can discharge a volume no more than 1% of the river flow. When the flows drop below 1000 ft^3/sec, the reclaimed water must be either disposed of through irrigation or stored in ponds.

The city owns 1,100 acres of land for effluent disposal with approximately 900 acres of permanent set sprinklers. The area is fenced and posted, and the site is used solely for disposal of reclaimed water and growing of cattle feed crops. The land is laid out with tailwater return systems so that no runoff leaves the city property. The city is leasing some of the ground for farming or grazing of sheep. The city's irrigation system is totally automatic, using irrigation controllers and solenoid valves. There are reclaimed-water-balancing reservoirs located throughout the project that have observation wells along their banks for monitoring percolation into the groundwater.

Although the farmers are not issued reclamation permits from the CRWQCB, they have a contract with the city that requires them to use the water according to SCDHS guidelines and to contain tailwater. The city does patrol and check the different users to see that the reclaimed water is being used according to state requirements.

The crops being irrigated with reclaimed water include field corn, Sudan grass, oats, and turnips, which are used as winter feed for sheep.

The farmers in the area growing feed crops for their dairy animals feel that the reclaimed water supplies approximately two-thirds of the nutrients required by their crop. At least one farmer is applying an additional 100 lb N/acre·year on approximately 230 acres of permanent pasture, where he is grazing about 2,000 head of sheep. This farmer has retained the services of an agronomist, who routinely reviews the irrigation water quality, cropping pattern, and soil chemistry and makes recommendations on nutrient requirements.

SONORA

Sonora is a small community located in the Sierra Nevada foothills about 50 miles east of Modesto. The Tuolumne County Water District No. 2 Water Treatment Facility is located southwest of the city.

The treatment plant collects wastewater from Sonora and several surrounding communities. The reclaimed water is discharged from the treatment plant into two ponds that primarily balance irrigation flows. After chlorination, the reclaimed water flows by gravity through several miles of pipeline to a 1,500-acre-ft storage reservoir. Turnouts along the pipeline are available for irrigation of forage crops, small pastures, and landscape areas. Water stored in the reservoir is distributed to other growers further downslope by another buried transmission pipeline.

Many farmers have signed up to use the reclaimed water, and at present, 1,129 acres are potentially available for irrigation. However, many of these areas are too steep to irrigate, which substantially reduces the potential acreage.

The treatment processes used at the plant include primary sedimentation, trickling filters, and chlorination. The plant capacity is 2.6 mgd. Average daily dry-weather flow averages 0.5 mgd, and maximum daily flow may be as high as 3.5 mgd in the winter and 1.0 mgd in the summer. The treatment plant has been in operation for only 8 years, and the long-term plant reliability has been found to be very good. No problems with reliability have been encountered yet. In case of treatment plant breakdown, a 14-day storage capacity is available.

The farmers in the area are satisfied with the reclaimed water, particularly because now that reclaimed water is available, small acreages that were previously not economical to farm are being developed into permanent pasture areas.

A few farmers have installed tailwater return systems to control runoff. As more areas are developed and the use of reclaimed water increases, tailwater return systems should be more common.

The use of reclaimed water for agricultural irrigation has solved a pollution problem. In the past, effluent was discharged into Woods

Creek, which flows into Don Pedro Reservoir. The reclaimed water was considered a source of pollution for the reservoir. With the construction of this project and the total usage of reclaimed water for irrigation, it is anticipated that no further degradation of water resources in Don Pedro Reservoir will occur.

VISALIA

The city of Visalia operates a wastewater reclamation plant that uses primary and secondary treatment. Secondary treatment consists of trickling filters, followed by activated sludge and chlorination. The treatment plant has a design capacity of 12.5 mgd, with an average flow of 7.6 mgd and a peak flow of 12 mgd. After the effluent leaves the chlorine contact chambers, it goes into large evaporation/ percolation ponds, which also serve as reservoirs. The effluent is discharged into Mill Creek, which is adjacent to the treatment plant. The city operates the treatment plant and discharges effluent under an NPDES permit that requires secondary treatment and chlorination before discharge.

Mill Creek is part of the Kaweah Delta Water Conservation District, which is the principal irrigation water purveyor for the area. The irrigation water in Mill Creek and other facilities served from Mill Creek is used as needed by the farmers. Farmers being served from the irrigation facility are not necessarily aware when reclaimed water is present, and some may not know that it is there at all. Irrigation water from this facility is used by the farmers to irrigate forage and fodder crops and landscape.

The agricultural community of the surrounding area is made up of both large and small farms. The crops grown in the area generally include milo, cotton, field corn, and alfalfa and are irrigated either from the Mill Creek canal system or from groundwater.

Some farmers along Mill Creek are using the effluent blended with their own well water at a ratio of about 1 to 1. Approximately 8 to 10 farmers regularly use water from Mill Creek. Under normal operation, the city sends water down the canal and diverts it into spreading basins within the watershed. The growers in the area have the ditch company's permission to change the head gates and bring the flow to their farm at any time.

The reclaimed water discharged into Mill Creek offers the farmers an alternate irrigation water source to the groundwater normally used for irrigation. The only cost in using this water is the cost of pumping it from the canal to their fields. Compared with the cost of pumping groundwater at a substantially high lift, the pumping cost could be significantly less when the use of reclaimed water in the Visalia area is viewed by the community as a water conservation measure and as an overall benefit to the community.

REFERENCES

1. Boyle Engineering Corporation. 1981. Evaluation of agricultural irrigation projects using reclaimed water. Prepared for California State Water Resources Control Board, Sacramento, Calif.

APPENDIX B

CALIFORNIA STATE WATER RESOURCES CONTROL BOARD

DIVISION OF WATER RIGHTS

PETITION FOR CHANGE

(FOR OWNERS OF WASTE WATER TREATMENT PLANTS <u>ONLY</u>)

PETITION FOR CHANGE OF □ POINT OF DISCHARGE OF TREATED WASTE WATER
□ PURPOSE OF USE OF TREATED WASTE WATER
□ PLACE OF USE OF TREATED WASTE WATER

State Water Resources Control Board
Division of Water Rights
P.O. Box 2000
Sacramento CA 95810

I HEREBY PETITION FOR CHANGES NOTED ABOVE AND SHOWN ON THE ACCOMPANYING MAP AND DESCRIBED AS FOLLOWS:

____
(Give tie by bearing and distance or by coordinate distances from some

____
government corner and the 40-acre subdivisions in which the new point

____
of discharge lies or acreage to be irrigated within each 40-acre tract).

GIVE REASON FOR PROPOSED CHANGE: ______________________________________

____

WASTE WATER WILL BE USED FOR ________________________________ *PURPOSES.*

I have access to the proposed new point of discharge or control the place of use proposed by virtue of

____
(ownership, lease, verbal, or written agreement)

____
(If by lease or agreement, state name and address of party or parties from whom access has been obtained.)

Are there any persons taking water from the stream between the old point of discharge and the new point of discharge ______ ______
yes *no*

Give names and adress, if answered yes, as well as other persons known to you who may be affected by the proposed change on the reverse side of this form or on an attached sheet.

This change does not involve water provided by a water service contract which prohibits my exclusive right to this treated waste water

_____ _____
yes *no*

No legal use of the discharge treated waste water will be affected

_____ _____
yes no

I declare under penalty of perjury that the above is true and correct to the best of my knowledge and belief.

Dated: _____________, 19 ___, at ________________________, California.

____

NOTE: Section 1547 of the Water Code requires a $10 filing fee with petitions for changes.

WR 22WW (4/14/83)

APPENDIX C

MINIMUM FILING FEE: $10.00
FILE ORIGINAL & ONE COPY
TYPE OR PRINT IN INK

STATE OF CALIFORNIA

State Water Resources Control Board
DIVISION OF WATER RIGHTS
901 P Street, Sacramento
P. O. Box 2000, Sacramento, CA 95810

APPLICATION to APPROPRIATE WATER

(For explanation of entries required, see booklet "How to File an Application to Appropriate Water in California")

Application No. ____________________

1. APPLICANT

I, ____
(Name of Applicant)

____
(Telephone Number where you may be reached between 8 a.m. and 5 p.m.—include area code)

____
(Address) (City or Town) (State) (Zip Code)

do hereby make application for a permit to appropriate the following described waters of the State of California, SUBJECT TO VESTED RIGHTS

2. SOURCE

a. The name of the source at the point of diversion is ______________________________
(If unnamed, state nature of source and that it IS unnamed)

tributary to ______________________________

b. In a normal year does the stream dry up at any point downstream from your project? YES ☐ NO ☐. If Yes, during what months is it usually dry? ______________________________

3. POINT of DIVERSION and REDIVERSION

a. The point of diversion will be in the County of ______________________________

b.

List all points giving coordinate distances from section corner or other tie as allowed by Board regulations	Point is within (40-acre Subdivision)	Section	Township	Range	Base and Meridan
	¼ of ¼				
	¼ of ¼				
	¼ of ¼				

c. Does applicant own the land at the point of diversion? YES ☐ NO ☐.

d. If applicant does not own land at point of diversion, state name and address of owner and state what steps have been taken to obtain right of access: ______________________________

4. PURPOSE of USE, AMOUNT and SEASON

a. State the purpose(s) for which water is to be appropriated, the amounts of water for each purpose and dates between which diversions will be made in the table below. Use gallons per day if rate is less than 0.025 cubic feet per second (approximately 16,000 gallons per day).

PURPOSE OF USE	DIRECT DIVERSION				STORAGE		
	AMOUNT		SEASON OF DIVERSION		AMOUNT	COLLECTION SEASON	
	RATE (Cubic feet per second or gallons per day)	Acre-feet per year	Beginning Date (Mo. & Day)	Ending Date (Mo. & Day)	Acre-feet per year	Beginning Date (Mo. & Day)	Ending Date (Mo. & Day)
Irrigation							
Domestic							
	________ (TOTAL)				________ (TOTAL)		

b. Total combined amount taken by direct diversion and storage during any one year will be ____________ acre-feet.

WR 1 (3/84)

5. JUSTIFICATION OF AMOUNT

a. IRRIGATION: Maximum acreage to be irrigated in any one year will be ______________ acres.

CROP	ACRES	METHOD OF IRRIGATION (Sprinklers, flooding, etc.)	ACRE-FEET (per year)	NORMAL SEASON	
				Beginning Date	Ending Date

b. DOMESTIC: The number of residences to be served ________. Separately owned: YES ☐ NO ☐
The total number of people to be served ________. Estimated daily use per person ______________ (gallons per day).
The total area of domestic lawns and gardens ____________ (square feet).
Miscellaneous domestic uses ______________ (Dust control area. Number and kind of domestic animals, etc.)

c. STOCKWATERING: Kind of Stock ____________. Maximum Number ________. Describe type of operation (feed lot, dairy, range, etc.)
____

d. RECREATIONAL: Type of recreation: Fishing ☐, Swimming ☐, Boating ☐, Other ☐.
(Submit "Supplement to Application", form SWRCB 1-1, for justification of amount for uses not listed above.)

6. DIVERSION WORK

a. Diversion will be by pumping from ______________ (sump, offset well, channel, reservoir, etc.). Pump discharge rate __________ (cfs/gpd). Horsepower ________.

b. Diversion will be by gravity by means of ______________ (pipe in unobstructed channel, pipe through dam, siphon, gate, etc.).

c. Estimated total cost of the diversion works proposed is ______________ (Give only cost of intake, or headworks, pumps, storage reservoirs, and main conduits.)

d. Main conduit from diversion point to first lateral or offstream storage reservoir:

CONDUIT (Pipe or channel)	MATERIAL (Kind of Pipe or channel lining)	CROSS SECTIONAL DIMENSION (Pipe diameter or ditch depth and top and bottom width	LENGTH (feet)	TOTAL LIFT OR FALL		CAPACITY (estimated)
				(feet)	(+ or −)	

e. The following applies to storage reservoirs: (For reservoirs having a capacity of 25 acre-feet or more, complete supplemental form SWRCB 1-1,

Name or number of reservoir, if any	DAM				RESERVOIR		
	Height of dam from streambed to spillway level (ft.)	Material construction	Dam Length (ft.)	Freeboard Dam height above spillway crest (ft.)	Approximate surface area when full (acres)	Approximate capacity (acre-feet)	Max. water depth

f. If water will be stored and the reservoir is not at the diversion point, the maximum rate of diversion to offstream storage will be ______ cfs.
Diversion to offstream storage will be amde by pumping ☐; gravity ☐.

7. PLACE OF USE

a. Applicant owns the land where the water will be used: YES ☐ NO ☐. Land is in joint ownership: YES ☐ NO ☐.
All joint owners should include their names as applicants and sign the application. If applicant does not own land where the water will be used; give name and address of owner and state what arrangements have been made with the owner.

____

____

USE IS WITHIN (40-acre Subdivision)	SECTION	TOWNSHIP	RANGE	BASE AND MERIDIAN	IF IRRIGATION	
					State Number of Acres	Presently cultivated (Yes or No)
¼ of ¼						
¼ of ¼						
¼ of ¼						
¼ of ¼						
¼ of ¼						
¼ of ¼						

If area is unsurveyed, state the location as if lines of the public land survey were projected. If space does not permit listing all 40-acre tracts, include on another sheet or state sections, townships and ranges, and show detail on map. For public districts or other extremely large areas, see Page 16 of instruction booklet "How to File and Application to Appropriate Water in California".

8. COMPLETION SCHEDULE

a. What year will work start ______________? b. What year will work be completed ______________?
c. What year will water be used to the full extent intended ____________? d. If complete, year of completion __________?

(ATTACH SUPPLEMENTAL SHEETS HERE)

9. GENERAL

a. What is the name of the post office most used by those living near the proposed point of diversion? ____________

b. Does any part of the place of use comprise a subdivision on file with the State Department of Real Estate? YES ☐ NO ☐. If Yes, state name of subdivision ____________ If No, is subdivision of these lands contemplated? YES ☐ NO ☐. Is it planned to individually meter each service connection? YES ☐ NO ☐. If Yes, when? ____________

c. Have you consulted the California Department of Fish and Game concerning this proposed project? YES ☐ NO ☐. If Yes, state the Department's opinion concerning the potential effects of your proposed project on fish and other wildlife and state measures required for mitigation ____________

If No, state the effects on fish and other wildlife you foresee as potentially arising from your proposed project. ____________

d. Please name other public agencies, if any, from which you have obtained or are required to obtain approvals regarding this project: ____________

e. What are the names and addresses of diverters of water from the source of supply downstream from the proposed point of diversion? ____________

f. Is the source used for navigation, including use by pleasure boats, for a significant part of each year at the point of diversion, or does the source substantially contribute to a waterway which is used for navigation, including use by pleasure boats? ____________

10. EXISTING WATER RIGHT

Do you claim an existing right for the use of all or part of the water sought by this application? YES ☐ NO ☐

If yes, complete table below

Nature of Rights (riparian, appropriative, groundwater.)	Year of First Use	Purpose of use made in recent years including amount, if known	Season of Use	Source	Location of Point of Diversion

11. AUTHORIZED AGENT (Optional)

With respect to: ☐ All matters concerning this water right application, ☐ those matters designated as follows: ____________

Name ____________ Address ____________

____________ Zip Code: ____________

(Telephone No. of agent between 8 a.m. and 5 p.m.)

is authorized to act on my behalf as my agent.

12. SIGNATURE of APPLICANT

I (we) declare under penalty of perjury that the above is true and correct to the best of my (our) knowledge and belief.

Dated ____________ 19 ____, at ____________, California

Ms. Mr.
Miss, Mrs. ____________
(Signature of applicant) (Refer to Section 671 of the Board's regulations)

If applicants are members of the same family (i.e., husband, wife, mother, father, son, brother, sister, etc.) or reside at the same address, please indicate their relationship:

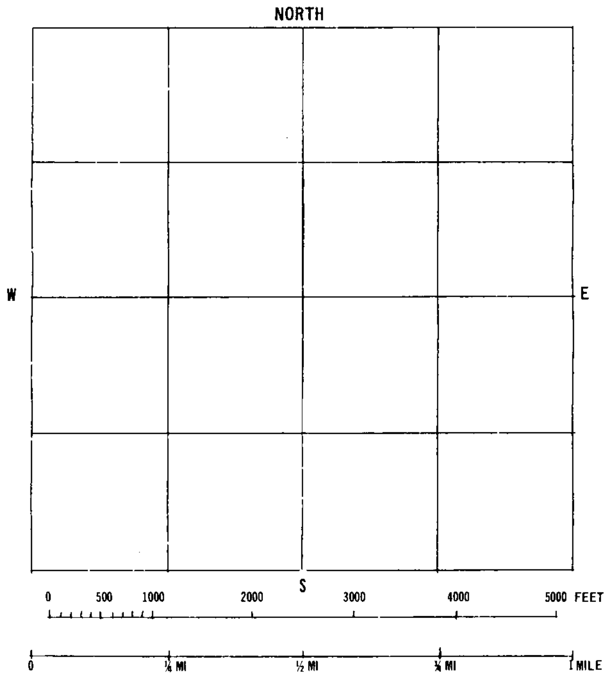
Ms. Mr.
Miss, Mrs. ____________
(Signature of applicant) (Refer to Section 671 of the Board's regulations)

Additional information needed for preparation of this application may be found in the leaflet entitled "HOW TO FILE AN APPLICATION TO APPROPRIATE WATER IN CALIFORNIA". If there is insufficient space for answers in this form, attach extra sheets. Please cross reference all remarks to the numbered item to which they may refer. Send application in duplicate to the STATE WATER RESOURCES CONTROL BOARD, DIVISION OF WATER RIGHTS, P. O. Box 2000, Sacramento, CA 95810, with $10 minimum filing fee.

13. Application Map

(Please complete legibly, with as much detail as possible)
(See example in instruction booklet)

SECTION(S) ________________ TOWNSHIP __________; RANGE _______; _____ B&M



(1) Show location of the spring or stream, and give name,
(2) Show location of the main ditch or pipe line.
(3) Indicate clearly the proposed place of use of the water.
(4) Locate and describe the point of diversion (i.e., the point at which water is to be taken from the stream or spring) in the following way: Begin at the most convenient known corner of the public land survey, such as a section or quarter section corner (if on unsurveyed land more than two miles from a section corner, begin at a mark or some natural object or permanent monument that can be readily found and recognized) and measure directly north or south until opposite the point which it is desired to locate; then measure directly east or west to the desired point. Show these distances in figures on the map as shown in the instructions.

14. Environmental Information

An Environmental Information form provided by the State Water Resources Control Board should be completed and attached to this application.

APPENDIX D

MEMORANDUM OF UNDERSTANDING BETWEEN THE WALNUT VALLEY WATER DISTRICT (WALNUT) AND THE ROWLAND AREA COUNTY WATER DISTRICT (ROWLAND) RELATING TO THE TERMS AND CONDITIONS OF RECLAIMED WATER SERVICE FOR EXISTING AND FUTURE CUSTOMERS WITHIN THE ROWLAND SERVICE AREA

This is to outline the concepts and considerations under which Rowland will sell reclaimed water to customers within their service area and under which Walnut will provide Rowland with reclaimed water.

1. Walnut is providing, by separate agreement, a commitment from the City of Pomona for the supply of tertiary treated effluent. The quality, quantity and reliability of that supply are determined within that agreement. Walnut will receive reclaimed water from the City of Pomona at a point of delivery as provided within their agreement. This point of delivery will be the western terminus of the North Side line, approximately at its intersection with Grand Avenue.

2. Reclaimed water at the point of delivery to Walnut shall be at hydrostatic pressure which is available. Static head at the point of delivery is 144 feet, which is the difference in elevation between the effluent structure at the Pomona Water Renovation Plant and the point of delivery to Walnut.

3. Walnut agrees to supply reclaimed water from the Pomona WRP to Rowland for use by its customers.

4. Walnut agrees to supply reclaimed water to Rowland at a wholesale price. The difference between the wholesale price paid by Rowland and the retail price paid by customers shall be at least sufficient to fund Rowland's costs for meter reading, customer billing and meter maintenance and replacement.

5. Walnut agrees to provide said reclaimed water to Rowland and Rowland agrees to purchase said reclaimed water from Walnut for a term not less than 15 years.

6. Walnut agrees to provide reclaimed water to Rowland at such time as Walnut completes construction of all facilities required for the delivery of reclaimed water to the end use customers. Walnut shall coordinate its construction schedule with Rowland to provide reasonable notice of its intent to deliver reclaimed water.

7. Walnut agrees to responsibility for the provision of design, construction and financing for a complete reclaimed water system inclusive of transmission, distribution and appurtenant facilities as required, exclusive of service meters, and piping to customer's property.

8. Rowland agrees to responsibility for customer meter reading and collection of charges from said Rowland customers. Rowland agrees to fund and provide for meter and service installation and maintenance and replacement of customer meters.

9. Walnut agrees to fund and provide for operation, maintenance and replacement of transmission, distribution and appurtenant facilities except for customer meters.

APPENDIX E

SAMPLE CLAUSES LIMITING AND INDEMNIFYING SUPPLIER LIABILITY

A WORD OF CAUTION:

The following warranty, disclaimer, remedy limitation, and indemnity clauses are technically sufficient under the Uniform Commercial Code and the California Commercial Code. They are modeled on language that has been tested and upheld in litigation concerning other commercial ventures. There has been no courtroom test of such clauses in wastewater supply contracts, however. The author (C. S. Richardson) therefore DISCLAIMS ANY IMPLIED WARRANTY OF FITNESS FOR THE PARTICULAR PURPOSE OF WASTEWATER SUPPLY CONTRACTS.

SAMPLE CLAUSES LIMITING AND INDEMNIFYING SUPPLIER LIABILITY:

SECTION _____: LIABILITY AND INSURANCE

A. WARRANTY AND DISCLAIMER AGREEMENTS

1. LIMITED WARRANTY OF WASTEWATER QUALITY

   (name of supplier) warrants that the wastewater delivered under this contract will comply with the physical and bacteriological requirements for the land disposition of treated wastewater imposed now and in the future by the California State Department of Health Services, the ________________ Regional Water Quality Control Board, and any agency having jurisdiction over such requirements during the term of this contract.

2. DISCLAIMER OF ALL OTHER WARRANTIES

   The water quality warranty set forth above is the SOLE WARRANTY extended by the Supplier for wastewater delivered under this contract. ORAL STATEMENTS BY THE PERSONNEL OF THE SUPPLIER DO NOT CONSTITUTE WARRANTIES. The supplier's agents and employees are not authorized to make warranties about the wastewater delivered under this contract. The buyer will not rely on any oral statements or written documents not expressly incorporated into this written contract. The entire contract is embodied in this writing and NO WARRANTIES ARE GIVEN beyond those set forth in this contract at Section ____.A.1.

The Supplier EXPRESSLY DISCLAIMS ANY IMPLIED WARRANTY OF MERCHANTABILITY AND ANY IMPLIED WARRANTY OF FITNESS FOR A PARTICULAR PURPOSE AND ALL OTHER EXPRESS AND IMPLIED WARRANTIES.

(Buyer should initial this section) ______

B. LIMITATION OF REMEDIES FOR BREACH OF WASTEWATER QUALITY WARRANTY

1. LIMITED REMEDY

Buyer may bring NO CLAIM against the Supplier, its agents, employees or assigns for failure to meet the wastewater quality standards imposed by regulatory agencies and warranted by this agreement excpet as provided by this section. This limited remedy will apply to negligent as well as non-negligent breach of warranty.

a. Buyer will be notified by Supplier by (specify means) of any deviation from the above specified wastewater quality standard.

b. Supplier will be liable to Buyer for damages to crops or land resulting from contact with below-standard wastewater which occurs before notification to Buyer, or before Buyer can reasonably prevent such contact after notification. Damages that may be claimed by Buyer will be limited as follows:

(Here the parties must agree upon a maximum valuation. This may be the actual loss in market value of the contaminated crop, as established by arbitration; the contract price of the water, limited to the agreed annual entitlement; or any valuation that will divide fairly the risk of the enterprise and give the buyer the substantial value of his bargain, considering the uncertainties both parties face at the outset.)

c. Buyer may bring NO CLAIM against Supplier for any damages resulting from contact with wastewater which occurs after notification has been received by him and he has had reasonable opportunity to prevent such contact.

d. TIME LIMIT FOR LEGAL ACTION ON BREACH OF WARRANTY: Any action alleging breach of warranty must be COMMENCED WITHIN ONE YEAR from the date the claim accrues, or be barred forever.

(Buyer should initial this section.)

2. EXCLUSION OF ALL OTHER REMEDIES

a. SOLE REMEDY: The parties agree that the remedy set forth above at Section____. B. will be the Buyer's SOLE AND EXCLUSIVE REMEDY against the Supplier for breach of the water quality warranty. The Buyer agrees that NO OTHER REMEDY WILL BE AVAILABLE TO HIM and that the wastewater Supplier will not be liable to him for incidental or consequential damages including lost income, lost use of land, lost sales, lost time, or liability incurred by Buyer due to default under contracts with other parties.

b. SUBSTANTIAL VALUE: The Buyer agrees that the bargained for price of the wastewater supplied under this contract is the result of a fair sharing of the risk between the Supplier and Buyer, and that this price justifies assuming the risk of loss due to failure to meet the water quality standards, as provided above. The Buyer therefore agrees that the exclusive remedy set forth at Section___.B. is fair and a reasonable remedy which gives the Buyer the substantial value of his bargain.

(Buyer should initial this section.)

C. INDEMNIFICATION AGREEMENT

(Alternative 1: third party liability is concentrated on the buyer.)

1. Buyer agrees to indemnify and defend the Supplier, its agents, employees, and assigns against all claims of any nature for loss, damage, or injury to all persons and property, arising out of any alleged defect in the wastewater or arising out of any operations and activities

under this wastewater supply contract. Buyer agrees to indemnify and defend Supplier even though the alleged wastewater defect, the loss, damage, or injury resulted from the active negligence, violation of law, breach of warranty, or strict tort liability of the Supplier.

2. Buyer agrees to name the Supplier as co-insured on a public liability insurance policy which will be obtained by the Buyer expressly to provide against liabilities arising from wastewater irrigation activities. Under this policy, the insurer must agree to indemnify and defend the Buyer and Supplier against all liabilities and expenses from claims for personal injury, death, property damage, and economic loss, resulting from any alleged product defect, act or omission by the Buyer or Seller, including the Supplier's active negligence and violation of law.

(Alternative 2: third party liability is allocated to Buyer or Supplier according to control over the source of risk. This alternative requires very explicit specification of facilities and activities in the exclusive or primary control of each party.)

1. Buyer agrees to indemnify and defend the Supplier, its agents, employees, and assigns against all claims of any nature for loss, damage, or injury to all persons and property, arising out of the acts or omissions of the Buyer, his agents or employees in using those facilities and conducting those activities identified in Section____ and____ as being under the sole or primary control of the Buyer. Buyer agrees to indemnify and defend the Supplier against such claims even though it may be alleged that the Supplier was actively negligent in entrusting such facilities or activities to the Buyer, or in monitoring, inspecting, or supervising such facilities or activities.

Buyer further agrees to indemnify and defend Supplier against all claims resulting from contact with wastewater which does not meet the water quality warranted at

Section___.A.1., when such contact occurs after notification to the Buyer and after the Buyer could reasonably act to prevent such contact following notification.

2. Buyer agrees to name the Supplier as co-insured on a public liability insurance policy which will be obtained by the Buyer expressly to provide against liabilities arising from wastewater irrigation activities. Under this policy, the insurer must agree to indemnify and defend the Buyer and Supplier against those liabilities described above at Section____C.1.

3. Supplier agrees to indemnify and defend the Buyer, his agents and employees against all claims of any nature for loss, damage, or injury to all persons and property, arising out of the acts or omissions of the Supplier, his agents, employees or assigns in using those facilities and conducting those activities identified in Section__ and___ as being under the sole or primary control of the Supplier.

   Supplier will indemnify and defend Buyer against all claims resulting from contact with wastewater which does not meet the water quality standards warranted at Section___. A.1., when such contact occurs before notification to Buyer or before Buyer could reasonably act to prevent such contact after notification.

4. Supplier agrees to name the Buyer as co-insured on a public liability insurance policy which will be obtained by the Supplier expressly to provide against liabilities arising from wastewater irrigation activities. Under this policy, the insurer must agree to indemnify and defend the Supplier and Buyer against those liabilities described above at Section___.C.3.

SECTION ___: OTHER PROVISIONS

A. SEVERABILITY

If any provision of this contract is held invalid or unconscionable in its application to any person or circumstances, such invalidity will not affect other provisions of this contract that can be given effect without the invalid or unconscionable provision. The provisions of this contract are severable.

B. WAIVER

If the Supplier agrees to waive any of the terms and conditions of this contract, such waiver will not be construed as a waiver of any succeeding breach of the same term or condition, or as a waiver of any other term or condition. A waiver by the Supplier as to any term or condition will not be construed as a course of performance.

C. MODIFICATION

No term or condition of this agreement may be waived or modified except by written agreement signed by the Supplier and Buyer.

D. TIME LIMIT FOR BRINGING LEGAL ACTION

Any action for breach of this contract and any action arising out of this contract must be brought within one year from the date the claim accrues, or be barred forever.

APPENDIX F

WASTEWATER RECLAMATION CRITERIA

An Excerpt from the

CALIFORNIA ADMINISTRATIVE CODE TITLE 22, DIVISION 4

ENVIRONMENTAL HEALTH

1978

STATE OF CALIFORNIA
DEPARTMENT OF HEALTH SERVICES
SANITARY ENGINEERING SECTION
2151 Berkeley Way, Berkeley 94704

INTENT OF REGULATIONS

The intent of these regulations is to establish acceptable levels of constituents of reclaimed water and to prescribe means for assurance of reliability in the production of reclaimed water in order to ensure that the use of reclaimed water for the specified purposes does not impose undue risks to health. The levels of constituents in combination with the means for assurance of reliability constitute reclamation criteria as defined in Section 13520 of the California Water Code.

As affirmed in Sections 13510 to 13512 of the California Water Code, water reclamation is in the best public interest and the policy of the State is to encourage reclamation. The reclamation criteria are intended to promote development of facilities which will assist in meeting water requirements of the State while assuring positive health protection. Appropriate surveillance and control of treatment facilities, distribution systems, and use areas must be provided in order to avoid health hazards. Precautions must be taken to avoid direct public contact with reclaimed waters which do not meet the standards specified in Article 5 for nonrestricted recreational impoundments.

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Article 10. Alternative Reliability Requirements for Uses Requiring Oxidized, Disinfected Wastewater or Oxidized, Coagulated, Clarified, Filtered, Disinfected Wastewater

CHAPTER 3. RECLAMATION CRITERIA

Article 1. Definitions

60301. Definitions. (a) **Reclaimed Water.** Reclaimed water means water which, as a result of treatment of domestic wastewater, is suitable for a direct beneficial use or a controlled use that would not otherwise occur.

(b) **Reclamation Plant.** Reclamation plant means an arrangement of devices, structures, equipment, processes and controls which produce a reclaimed water suitable for the intended reuse.

(c) **Regulatory Agency.** Regulatory agency means the California Regional Water Quality Control Board in whose jurisdiction the reclamation plant is located.

(d) **Direct Beneficial Use.** Direct beneficial use means the use of reclaimed water which has been transported from the point of production to the point of use without an intervening discharge to waters of the State.

(e) **Food Crops.** Food crops mean any crops intended for human consumption.

(f) **Spray Irrigation.** Spray irrigation means application of reclaimed water to crops by spraying it from orifices in piping.

(g) **Surface Irrigation.** Surface irrigation means application of reclaimed water by means other than spraying such that contact between the edible portion of any food crop and reclaimed water is prevented.

(h) **Restricted Recreational Impoundment.** A restricted recreational impoundment is a body of reclaimed water in which recreation is limited to fishing, boating, and other non-body-contact water recreation activities.

(i) **Nonrestricted Recreational Impoundment.** A nonrestricted recreational impoundment is an impoundment of reclaimed water in which no limitations are imposed on body-contact water sport activities.

(j) **Landscape Impoundment.** A landscape impoundment is a body of reclaimed water which is used for aesthetic enjoyment or which otherwise serves a function not intended to include public contact.

(k) **Approved Laboratory Methods.** Approved laboratory methods are those specified in the latest edition of "Standard Methods for the Examination of Water and Wastewater", prepared and published jointly by the American Public Health Association, the American Water Works Association, and the Water Pollution Control Federation and which are conducted in laboratories approved by the State Department of Health.

(l) **Unit Process.** Unit process means an individual stage in the wastewater treatment sequence which performs a major single treatment operation.

(m) **Primary Effluent.** Primary effluent is the effluent from a wastewater treatment process which provides removal of sewage solids so that it contains not more than 0.5 milliliter per liter per hour of settleable solids as determined by an approved laboratory method.

(n) **Oxidized Wastewater.** Oxidized wastewater means wastewater in which the organic matter has been stabilized, is nonputrescible, and contains dissolved oxygen.

(o) **Biological Treatment.** Biological treatment means methods of wastewater treatment in which bacterial or biochemical action is intensified as a means of producing an oxidized wastewater.

(p) **Secondary Sedimentation.** Secondary sedimentation means the removal by gravity of settleable solids remaining in the effluent after the biological treatment process.

(q) **Coagulated Wastewater.** Coagulated wastewater means oxidized wastewater in which colloidal and finely divided suspended matter have been destabilized and agglomerated by the addition of suitable floc-forming chemicals or by an equally effective method.

(r) **Filtered Wastewater.** Filtered wastewater means an oxidized, coagulated, clarified wastewater which has been passed through natural undisturbed soils or filter media, such as sand or diatomaceous earth, so that the turbidity as determined by an approved laboratory method does not exceed an average operating turbidity of 2 turbidity units and does not exceed 5 turbidity units more than 5 percent of the time during any 24-hour period.

(s) **Disinfected Wastewater.** Disinfected wastewater means wastewater in which the pathogenic organisms have been destroyed by chemical, physical or biological means.

(t) **Multiple Units.** Multiple units means two or more units of a treatment process which operate in parallel and serve the same function.

(u) **Standby Unit Process.** A standby unit process is an alternate unit process or an equivalent alternative process which is maintained in operable condition and which is capable of providing comparable treatment for the entire design flow of the unit for which it is a substitute.

(v) **Power Source.** Power source means a source of supplying energy to operate unit processes.

(w) **Standby Power Source.** Standby power source means an automatically actuated self-starting alternate energy source maintained in immediately operable condition and of sufficient capacity to provide necessary service during failure of the normal power supply.

(x) **Standby Replacement Equipment.** Standby replacement equipment means reserve parts and equipment to replace broken-down or worn-out units which can be placed in operation within a 24-hour period.

(y) **Standby Chlorinator.** A standby chlorinator means a duplicate chlorinator for reclamation plants having one chlorinator and a duplicate of the largest unit for plants having multiple chlorinator units.

(z) **Multiple Point Chlorination.** Multiple point chlorination means that chlorine will be applied simultaneously at the reclamation plant and at subsequent chlorination stations located at the use area and/or some intermediate point. It does not include chlorine application for odor control purposes.

(aa) **Alarm.** Alarm means an instrument or device which continuously monitors a specific function of a treatment process and automatically gives warning of an unsafe or undesirable condition by means of visual and audible signals.

(bb) **Person.** Person also includes any private entity, city, county, district, the State or any department or agency thereof.

NOTE: Authority cited: Section 208, Health and Safety Code and Section 13521, Water Code. Reference: Section 13521, Water Code.

History: 1. New Chapter 4 (§§ 60301–60357, not consecutive) filed 4-2-75; effective thirtieth day thereafter (Register 75, No. 14).

2. Renumbering of Chapter 4 (Sections 60301–60357, not consecutive) to Chapter 3 (Sections 60301–60357, not consecutive), filed 10-14-77; effective thirtieth day thereafter (Register 77, No. 42).

Article 2. Irrigation of Food Crops

60303. Spray Irrigation. Reclaimed water used for the spray irrigation of food crops shall be at all times an adequately disinfected, oxidized, coagulated, clarified, filtered wastewater. The wastewater shall be considered adequately disinfected if at some location in the treatment process the median number of coliform organisms does not exceed 2.2 per 100 milliliters and the number of coliform organisms does not exceed 23 per 100 milliliters in more than one sample within any 30-day period. The median value shall be determined from the bacteriological results of the last 7 days for which analyses have been completed.

60305. Surface Irrigation. (a) Reclaimed water used for surface irrigation of food crops shall be at all times an adequately disinfected, oxidized wastewater. The wastewater shall be considered adequately disinfected if at some location in the treatment process the median number of coliform organisms does not exceed 2.2 per 100 milliliters, as determined from the bacteriological results of the last 7 days for which analyses have been completed.

(b) Orchards and vineyards may be surface irrigated with reclaimed water that has the quality at least equivalent to that of primary effluent provided that no fruit is harvested that has come in contact with the irrigating water or the ground.

60307. Exceptions. Exceptions to the quality requirements for reclaimed water used for irrigation of food crops may be considered by the State Department of Health on an individual case basis where the reclaimed water is to be used to irrigate a food crop which must undergo extensive commercial, physical or chemical processing sufficient to destroy pathogenic agents before it is suitable for human consumption.

Article 3. Irrigation of Fodder, Fiber, and Seed Crops

60309. Fodder, Fiber, and Seed Crops. Reclaimed water used for the surface or spray irrigation of fodder, fiber, and seed crops shall have a level of quality no less than that of primary effluent.

60311. Pasture for Milking Animals. Reclaimed water used for the irrigation of pasture to which milking cows or goats have access shall be at all times an adequately disinfected, oxidized wastewater. The wastewater shall be considered adequately disinfected if at some location in the treatment process the median number of coliform organisms does not exceed 23 per 100 milliliters, as determined from the bacteriological results of the last 7 days for which analyses have been completed.

Article 4. Landscape Irrigation

60313. Landscape Irrigation. (a) Reclaimed water used for the irrigation of golf courses, cemeteries, freeway landscapes, and landscapes in other areas where the public has similar access or exposure shall be at all times an adequately disinfected, oxidized wastewater. The wastewater shall be considered adequately disinfected if the median number of coliform organisms in the effluent does not exceed 23 per 100 milliliters, as determined from the bacteriological results of the last 7 days for which analyses have been completed, and the number of coliform organisms does not exceed 240 per 100 milliliters in any two consecutive samples.

(b) Reclaimed water used for the irrigation of parks, playgrounds, schoolyards, and other areas where the public has similar access or exposure shall be at all times an adequately disinfected, oxidized, coagulated, clarified, filtered wastewater or a wastewater treated by a sequence of unit processes that will assure an equivalent degree of treatment and reliability. The wastewater shall be considered adequately disinfected if the median number of coliform organisms in the effluent does not exceed 2.2 per 100 milliliters, as determined from the bacteriological results of the last 7 days for which analyses have been completed, and the number of coliform organisms does not exceed 23 per 100 milliliters in any sample.

NOTE: Authority cited: Section 208, Health and Safety Code and Section 13521, Water Code. Reference: Section 13520, Water Code.

History: 1. Amendment filed 9-22-78; effective thirtieth day thereafter (Register 78, No. 38).

Article 5. Recreational Impoundments

60315. Nonrestricted Recreational Impoundment. Reclaimed water used as a source of supply in a nonrestricted recreational impoundment shall be at all times an adequately disinfected, oxidized, coagulated, clarified, filtered wastewater. The wastewater shall be considered adequately disinfected if at some location in the treatment process the median number of coliform organisms does not exceed 2.2 per 100 milliliters and the number of coliform organisms does not exceed 23 per 100 milliliters in more than one sample within any 30-day period. The median value shall be determined from the bacteriological results of the last 7 days for which analyses have been completed.

60317. Restricted Recreational Impoundment. Reclaimed water used as a source of supply in a restricted recreational impoundment shall be at all times an adequately disinfected, oxidized wastewater. The wastewater shall be considered adequately disinfected if at some location in the treatment process the median number of coliform organisms does not exceed 2.2 per 100 milliliters, as determined from the bacteriological results of the last 7 days for which analyses have been completed.

60319. Landscape Impoundment. Reclaimed water used as a source of supply in a landscape impoundment shall be at all times an adequately disinfected, oxidized wastewater. The wastewater shall be considered adequately disinfected if at some location in the treatment process the median number of coliform organisms does not exceed 23 per 100 milliliters, as determined from the bacteriological results of the last 7 days for which analyses have been completed.

Article 5.1. Groundwater Recharge

60320. Groundwater Recharge. (a) Reclaimed water used for groundwater recharge of domestic water supply aquifers by surface spreading shall be at all times of a quality that fully protects public health. The State Department of Health Services' recommendations to the Regional Water Quality Control Boards for proposed groundwater recharge projects and for expansion of existing projects will be made on an individual case basis where the use of reclaimed water involves a potential risk to public health.

(b) The State Department of Health Services' recommendations will be based on all relevant aspects of each project, including the following factors: treatment provided; effluent quality and quantity; spreading area operations; soil characteristics; hydrogeology; residence time; and distance to withdrawal.

(c) The State Department of Health Services will hold a public hearing prior to making the final determination regarding the public health aspects of each groundwater recharge project. Final recommendations will be submitted to the Regional Water Quality Control Board in an expeditious manner.

NOTE: Authority cited: Section 208, Health and Safety Code and Section 13521, Water Code. Reference: Section 13520, Water Code.

History: 1. New Article 5.1 (Section 60320) filed 9-22-78; effective thirtieth day thereafter (Register 78, No. 38).

Article 5.5. Other Methods of Treatment

60320.5. Other Methods of Treatment. Methods of treatment other than those included in this chapter and their reliability features may be accepted if the applicant demonstrates to the satisfaction of the State Department of Health that the methods of treatment and reliability features will assure an equal degree of treatment and reliability.

NOTE: Authority cited: Section 208, Health and Safety Code and Section 13521, Water Code. Reference: Section 13520, Water Code.

History: 1. Renumbering of Article 11 (Section 60357) to Article 5.5 (Section 60320.5) filed 9-22-78; effective thirtieth day thereafter (Register 78, No. 38).

Article 6. Sampling and Analysis

60321. **Sampling and Analysis.** (a) Samples for settleable solids and coliform bacteria, where required, shall be collected at least daily and at a time when wastewater characteristics are most demanding on the treatment facilities and disinfection procedures. Turbidity analysis, where required, shall be performed by a continuous recording turbidimeter.

(b) For uses requiring a level of quality no greater than that of primary effluent, samples shall be analyzed by an approved laboratory method of settleable solids.

(c) For uses requiring an adequately disinfected, oxidized wastewater, samples shall be analyzed by an approved laboratory method for coliform bacteria content.

(d) For uses requiring an adequately disinfected, oxidized, coagulated, clarified, filtered wastewater, samples shall be analyzed by approved laboratory methods for turbidity and coliform bacteria content.

Article 7. Engineering Report and Operational Requirements

60323. **Engineering Report.** (a) No person shall produce or supply reclaimed water for direct reuse from a proposed water reclamation plant unless he files an engineering report.

(b) The report shall be prepared by a properly qualified engineer registered in California and experienced in the field of wastewater treatment, and shall contain a description of the design of the proposed reclamation system. The report shall clearly indicate the means for compliance with these regulations and any other features specified by the regulatory agency.

(c) The report shall contain a contingency plan which will assure that no untreated or inadequately-treated wastewater will be delivered to the use area.

60325. **Personnel.** (a) Each reclamation plant shall be provided with a sufficient number of qualified personnel to operate the facility effectively so as to achieve the required level of treatment at all times.

(b) Qualified personnel shall be those meeting requirements established pursuant to Chapter 9 (commencing with Section 13625) of the Water Code.

60327. **Maintenance.** A preventive maintenance program shall be provided at each reclamation plant to ensure that all equipment is kept in a reliable operating condition.

60329. **Operating Records and Reports.** (a) Operating records shall be maintained at the reclamation plant or a central depository within the operating agency. These shall include: all analyses specified in the reclamation criteria; records of operational problems, plant and equipment breakdowns, and diversions to emergency storage or disposal; all corrective or preventive action taken.

(b) Process or equipment failures triggering an alarm shall be recorded and maintained as a separate record file. The recorded information shall include the time and cause of failure and corrective action taken.

(c) A monthly summary of operating records as specified under (a) of this section shall be filed monthly with the regulatory agency.

(d) Any discharge of untreated or partially treated wastewater to the use area, and the cessation of same, shall be reported immediately by telephone to the regulatory agency, the State Department of Health, and the local health officer.

60331. Bypass. There shall be no bypassing of untreated or partially treated wastewater from the reclamation plant or any intermediate unit processes to the point of use.

Article 8. General Requirements of Design

60333. Flexibility of Design. The design of process piping, equipment arrangement, and unit structures in the reclamation plant must allow for efficiency and convenience in operation and maintenance and provide flexibility of operation to permit the highest possible degree of treatment to be obtained under varying circumstances.

60335. Alarms. (a) Alarm devices required for various unit processes as specified in other sections of these regulations shall be installed to provide warning of:

(1) Loss of power from the normal power supply.
(2) Failure of a biological treatment process.
(3) Failure of a disinfection process.
(4) Failure of a coagulation process.
(5) Failure of a filtration process.
(6) Any other specific process failure for which warning is required by the regulatory agency.

(b) All required alarm devices shall be independent of the normal power supply of the reclamation plant.

(c) The person to be warned shall be the plant operator, superintendent, or any other responsible person designated by the management of the reclamation plant and capable of taking prompt corrective action.

(d) Individual alarm devices may be connected to a master alarm to sound at a location where it can be conveniently observed by the attendant. In case the reclamation plant is not attended full time, the alarm(s) shall be connected to sound at a police station, fire station or other full-time service unit with which arrangements have been made to alert the person in charge at times that the reclamation plant is unattended.

60337. Power Supply. The power supply shall be provided with one of the following reliability features:

(a) Alarm and standby power source.

(b) Alarm and automatically actuated short-term retention or disposal provisions as specified in Section 60341.

(c) Automatically actuated long-term storage or disposal provisions as specified in Section 60341.

Article 9. Alternative Reliability Requirements for Uses Permitting Primary Effluent

60339. Primary Treatment. Reclamation plants producing reclaimed water exclusively for uses for which primary effluent is permitted shall be provided with one of the following reliability features:

(a) Multiple primary treatment units capable of producing primary effluent with one unit not in operation.

(b) Long-term storage or disposal provisions as specified in Section 60341.

Article 10. Alternative Reliability Requirements for Uses Requiring Oxidized, Disinfected Wastewater or Oxidized, Coagulated, Clarified, Filtered, Disinfected Wastewater

60341. Emergency Storage or Disposal. (a) Where short-term retention or disposal provisions are used as a reliability feature, these shall consist of facilities reserved for the purpose of storing or disposing of untreated or partially treated wastewater for at least a 24-hour period. The facilities shall include all the necessary diversion devices, provisions for odor control, conduits, and pumping and pump back equipment. All of the equipment other than the pump back equipment shall be either independent of the normal power supply or provided with a standby power source.

(b) Where long-term storage or disposal provisions are used as a reliability feature, these shall consist of ponds, reservoirs, percolation areas, downstream sewers leading to other treatment or disposal facilities or any other facilities reserved for the purpose of emergency storage or disposal of untreated or partially treated wastewater. These facilities shall be of sufficient capacity to provide disposal or storage of wastewater for at least 20 days, and shall include all the necessary diversion works, provisions for odor and nuisance control, conduits, and pumping and pump back equipment. All of the equipment other than the pump back equipment shall be either independent of the normal power supply or provided with a standby power source.

(c) Diversion to a less demanding reuse is an acceptable alternative to emergency disposal of partially treated wastewater provided that the quality of the partially treated wastewater is suitable for the less demanding reuse.

(d) Subject to prior approval by the regulatory agency, diversion to a discharge point which requires lesser quality of wastewater is an acceptable alternative to emergency disposal of partially treated wastewater.

(e) Automatically actuated short-term retention or disposal provisions and automatically actuated long-term storage or disposal provisions shall include, in addition to provisions of (a), (b), (c), or (d) of this section, all the necessary sensors, instruments, valves and other devices to enable fully automatic diversion of untreated or partially treated wastewater to approved emergency storage or disposal in the event of failure of a treatment process, and a manual reset to prevent automatic restart until the failure is corrected.

60343. Primary Treatment. All primary treatment unit processes shall be provided with one of the following reliability features:

(a) Multiple primary treatment units capable of producing primary effluent with one unit not in operation.

(b) Standby primary treatment unit process.

(c) Long-term storage or disposal provisions.

60345. Biological Treatment. All biological treatment unit processes shall be provided with one of the following reliability features:

(a) Alarm and multiple biological treatment units capable of producing oxidized wastewater with one unit not in operation.

(b) Alarm, short-term retention or disposal provisions, and standby replacement equipment.

(c) Alarm and long-term storage or disposal provisions.

(d) Automatically actuated long-term storage or disposal provisions.

60347. Secondary Sedimentation. All secondary sedimentation unit processes shall be provided with one of the following reliability features:

(a) Multiple sedimentation units capable of treating the entire flow with one unit not in operation.

(b) Standby sedimentation unit process.

(c) Long-term storage or disposal provisions.

60349. Coagulation.

(a) All coagulation unit processes shall be provided with the following mandatory features for uninterrupted coagulant feed:

(1) Standby feeders,

(2) Adequate chemical stowage and conveyance facilities,

(3) Adequate reserve chemical supply, and

(4) Automatic dosage control.

(b) All coagulation unit processes shall be provided with one of the following reliability features:

(1) Alarm and multiple coagulation units capable of treating the entire flow with one unit not in operation;

(2) Alarm, short-term retention or disposal provisions, and standby replacement equipment;

(3) Alarm and long-term storage or disposal provisions;

(4) Automatically actuated long-term storage or disposal provisions, or

(5) Alarm and standby coagulation process.

60351. Filtration. All filtration unit processes shall be provided with one of the following reliability features:

(a) Alarm and multiple filter units capable of treating the entire flow with one unit not in operation.

(b) Alarm, short-term retention or disposal provisions and standby replacement equipment.

(c) Alarm and long-term storage or disposal provisions.
(d) Automatically actuated long-term storage or disposal provisions.
(e) Alarm and standby filtration unit process.

60353. Disinfection.

(a) All disinfection unit processes where chlorine is used as the disinfectant shall be provided with the following features for uninterrupted chlorine feed:

(1) Standby chlorine supply,
(2) Manifold systems to connect chlorine cylinders,
(3) Chlorine scales, and
(4) Automatic devices for switching to full chlorine cylinders.

Automatic residual control of chlorine dosage, automatic measuring and recording of chlorine residual, and hydraulic performance studies may also be required.

(b) All disinfection unit processes where chlorine is used as the disinfectant shall be provided with one of the following reliability features:

(1) Alarm and standby chlorinator;
(2) Alarm, short-term retention or disposal provisions, and standby replacement equipment;
(3) Alarm and long-term storage or disposal provisions;
(4) Automatically actuated long-term storage or disposal provisions; or
(5) Alarm and multiple point chlorination, each with independent power source, separate chlorinator, and separate chlorine supply.

60355. Other Alternatives to Reliability Requirements. Other alternatives to reliability requirements set forth in Articles 8 to 10 may be accepted if the applicant demonstrates to the satisfaction of the State Department of Health that the proposed alternative will assure an equal degree of reliability.

APPENDIX G

CONVERSION TABLE

A	B[a]	To convert A to B, multiply A by:
Length		
foot	meter	0.3048
inch	centimeter	2.54
Area		
acre	hectare (ha)	0.4046
acre	square foot	43,560
square foot	square meter	0.0929
Volume		
gallon	liter (L)	3.785
gallon	cubic meter	0.003785
acre-ft	gallon (gal)	325,850
acre-ft	cubic meter	1233.5
liter	cubic meter	1000
Flow rate		
million gallons/day (mgd)	cubic meter/sec	0.0438
million gallons/day	acre-ft/year	1120.0
million gallons/day	acre-inch/day	36.828
gallons/minute	liter/second	0.06308
gallons/minute	acre-inch/day	0.5303
gallons/minute·square foot	liter/square meter·sec	0.67902
cubic feet/second	liter/second	28.450
cubic feet/second	acre-inch/day	23.8
inch/week	centimeter/week	2.54
Concentration		
parts per million (ppm)	milligram/kilogram	1.00
milligram/liter	gram/cubic meter	1.00
parts per billion (ppb)	milligram/liter	0.001
millequivalents/liter	milligram/liter	gram equivalent weight
Mass or weight		
pound	kilogram (kg)	0.4536
ton (U.S.)	ton (metric)	0.9072
Yield		
pounds/acre	kilogram/hectare	1.12
ton (U.S.)/acre	ton (metric)/hectare	2.24
Pressure		
pound/square inch	Pascal (Pa)	6895

A	B[a]	To convert A to B, multiply A by:
Electrical conductivity		
millimhos/centimeter (mmho/cm)	deciSiemens/meter (dS/m)	1.00
Temperature		
degrees Fahrenheit, °F	degrees Celsius, °C	5/9 (°F-32)
degrees Celsius, °C	degrees Fahrenheit, °F	9/5 (°C)+32

a. Most of these are SI units or derivatives of SI units. Systeme Internationale (SI) is a universal measurement language which makes use of only 7 base units and also uses derived units which are expressed algebraically in terms of base units. The base units are: meter (m), kilogram (kg), second (s), ampere (A), candela (cd), kelvin (K) and mole (mole).

APPENDIX H
GLOSSARY

activated sludge process - A biological wastewater treatment process in which a mixture of wastewater and activated sludge is agitated and aerated.

advanced wastewater treatment - Any physical, chemical, or biological treatment process used to accomplish a degree of treatment greater than that achieved by secondary treatment. Usually implies removal of nutrients and a high percentage of suspended solids.

alkalinity - The capacity of water to neutralize acids; a property imparted by carbonates, bicarbonates, hydroxides, and occasionally borates, silicates, and phosphates. It is expressed in milligrams of equivalent calcium carbonate per liter.

available water - The portion of water in a soil that can be readily absorbed by plant roots. Considered by most workers to be that water held in the soil against a pressure of up to approximately 15 bars. See **field capacity, permanent wilting point**, and **soil moisture tension**.

BOD - (1) Biochemical oxygen demand. The quantity of oxygen used in the biochemical oxidation of organic matter in a specified time, at a specified temperature, and under specified conditions. (2) A standard test used in assessing wastewater strength.

cation exchange capacity (CEC) - The sum of exchangeable cations that a soil can adsorb expressed in millequivalents per 100 grams of soil or in millimoles of positive charge per kilogram of soil. CEC is directly related to a soil's ability to retain cations against leaching. CEC is also used in calculating exchangeable sodium percentage (ESP) - a measure of excessive sodium hazard in the soil.

COD - Chemical oxygen demand. A quantitative measure of the amount of oxygen required for the chemical oxidation of carbonaceous (organic) material in wastewater using dichromate or permanganate salts as oxidants in a two-hour test.

denitrification - The biological conversion of nitrate or nitrite to gaseous N_2 or N_2O.

effluent - Partially or completely treated wastewater flowing out of a treatment plant, reservoir, or basin.

electrical conductivity (EC_w for water, EC_e for the soil saturation extract) - A measure of salinity expressed in millimhos per centimeter (mmho/cm) or decisiemens per meter (dS/m) at 25°C. Empirically related to total dissolved solids (in mg/L) divided by 640.

evapotranspiration (ET) - The combined loss of water from a given area and during a specified period of time by evaporation from the soil surface and by transpiration from plants. ET_o is reference ET defined as the ET from an extended surface of 3 to 6-inch tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water. E_p or E_{pan} is evaporation from a standard evaporation pan.

exchangeable sodium percentage (ESP) - The ratio (as percent) of exchangeable sodium to the remaining exchangeable cations in the soil. See **SAR**.

field capacity (FC) - The percentage of water (either weight or volume) remaining in a soil 2 or 3 days after having been saturated and after free drainage has practically ceased. This term is obsolete in technical work. For many soils, FC is in the range of 1/10 to 1/3 bar water potential. See **soil moisture tension**.

gypsum requirement - The quantity of gypsum or its equivalent required to reduce the exchangeable sodium fraction of a given increment of soil to an acceptable level (see Chapter 7).

horizon - A layer of soil differing from adjacent genetically related layers in properties such as color, structure, texture, consistency, pH, etc.

hydraulic conductivity - The rate of water flow in soil per unit gradient of hydraulic head or potential.

immobilization - The conversion of an element from the inorganic to the organic form in microbial or plant tissues. Often used to describe the conversion of nitrate or ammonium into organic forms in soil microorganisms.

infiltration - (1) The downward entry of water into soil. (2) The flow or movement of water through the pores of a soil or other porous medium. (3) The quantity of groundwater that leaks into a pipe through joints, porous walls, or breaks. (4) The entrance of water from the ground into a gallery.

infiltration rate - (1) A soil characteristic describing the maximum rate at which water can enter the soil under specified conditions, including the presence of excess water. It has the dimensions of velocity, i.e., inch/hr or cm/sec. Formerly, the infiltration capacity. (2) The rate, usually expressed in cubic feet per second or million gallons per day per mile of waterway, at which groundwater enters an infiltration ditch or gallery, drain, sewer, or other underground conduit.

infiltrometer - Any of several devices for measuring the rate of entry of water into a soil.

influent - Wastewater flowing into a treatment plant, or treatment process.

land application - The recycling, treatment, or disposal of wastewater or wastewater solids to the land under controlled conditions.

land disposal - Application of raw or treated wastewater, sludges, or solid waste to soils and/or substrata without production of usable agricultural products. (See also **land treatment**).

land treatment - Irrigation with partially treated wastewater on land; additional treatment is provided by soil, microorganisms, and crops which are grown to utilize nutrients. See also **land application**, **land disposal**.

leaching fraction (LF)- The fraction of water applied to soil that leaches below a depth of interest such as the rooting depth.

leaching requirement (LR) - The leaching fraction required to maintain average root zone salinity below a phytotoxic threshold value.

management allowed depletion (MAD) - The amount of water which the irrigator will allow to be depleted by evapotranspiration between irrigations, expressed either as a percent of available water in the root zone or a depth of water.

mineralization - The conversion of an element from an organic to an inorganic form (e.g., the conversion of organic nitrogen in wastewater to ammonium nitrogen by microbial decomposition).

overland flow - A type of land treatment in which water flows over the surface of vegetated land before entering some defined channel.

oxidation pond - A relatively shallow pond or basin in which biological oxidation is effected by natural or artificially accelerated transfer of oxygen (e.g., algae pond, lagoon).

pan - A horizon or layer in soil that is strongly compacted, indurated, or very high in clay content. **Caliche** is a pan cemented by calcium or magnesium carbonates. A **fragipan** is a natural pan in non-calcareous soils seemingly cemented when dry but when moist showing a moderate to weak brittleness.

permanent wilting point (PWP) -A plant physiology term referring to the soil water content at which plants wilt and do not recover. By convention, often considered to be the soil water content at -15 bars water potential. Actual PWP can vary greatly from this value.

permeability - The ease with which gas, liquids or plant roots penetrate or pass through a soil horizon.

pH - The degree of acidity or alkalinity, defined as the negative logarithm of hydrogen ion activity of water.

primary treatment - (1) The first major treatment in a wastewater treatment facility, usually sedimentation but not biological oxidation. (2) The removal of a substantial amount of suspended matter but little or no colloidal and dissolved matter. (3) Wastewater treatment processes usually consisting of clarification with or without chemical treatment to accomplish solid-liquid separation. See also **secondary treatment, tertiary treatment**.

rapid infiltration - A type of land treatment in which water is applied to relatively porous soil at rates far in excess of normal crop irrigation.

secondary treatment - (1) Generally, a level of treatment that produces removal efficiencies for BOD and suspended solids of 85%. (2) Sometimes used interchangeably with concept of biological wastewater treatment, particularly the activated sludge process. Commonly applied to treatment that consists chiefly of a biological process followed by clarification with separate sludge collection and handling.

slow rate land treatment process - A type of land treatment of wastewater. Wastewater is applied to a vegetated land surface with the applied wastewater being treated as it flows through the plant-soil matrix.

sodium adsorption ratio (R_{Na} or SAR) - A measure of the amount of sodium relative to the amount of calcium and magnesium in water or in a soil saturation extract. It is defined as follows:

$$R_{Na} \text{ or SAR} = \frac{Na}{\sqrt{(Ca + Mg)/2}}$$

where the quantities Na, Ca, and Mg are expressed in milliequivalent/liter. The SAR can be used to predict the exchangeable sodium percentage of a soil equilibrated with a given solution. A procedure for calculating an adjusted R_{Na} for waters high in bicarbonate is presented in Chapter 3.

soil moisture tension (or pressure) - The soil water content expressed as an equivalent negative pressure. It is equal to the equivalent pressure that must be applied to soil water to bring it to equilibrium, through a permeable membrane, with a pool of water of the same composition. Usually expressed in bars or atmospheres.

soil structure - The combination or arrangement of primary soil particles into secondary particles, aggregates, or peds. These secondary units are classified by soil morphologists on the basis of size, shape, and degree of distinctness.

reclaimed wastewater - Wastewater that, as a result of treatment, is suitable for a beneficial use.

soil texture - The relative proportions in a soil of sand, silt, and clay-sized mineral particles.

soil total water potential - The amount of work which must be done to transport a unit of pure water to the soil water isothermally and at atmospheric pressure. Comprised mainly of osmotic, gravitational, and capillary components.

soil water content -The amount of water lost from the soil upon drying to constant weight at 105°C, expressed as g water per g dry soil or cm^3 water per cm^3 bulk soil. In the field, water content is often expressed on a percent dry weight basis. This can lead to ambiguity when it is not stated whether a weight or volume basis is being used.

tertiary treatment - See **advanced wastewater treatment.**

total dissolved solids (TDS) - The sum of all dissolved solids in a water or wastewater and an expression of water salinity in mg/L. Empirically related to electrical conductivity (EC in dS/m) multiplied by 640.

trickling filter - A coarse filter used to provide secondary treatment of wastewater. A film of aerobic microorganisms on the filter media metabolizes the organic material in the wastewater trickling downward to underdrains; biofilm that sloughs off is subsequently removed by sedimentation.

wastewater irrigation - Land application of wastewater with the primary purpose of maximizing crop production per unit of water applied. Often used in a broader sense to mean land treatment and disposal of wastewater where maximum crop production is a secondary objective.

wastewater reclamation - The process of treating wastewater to produce water for beneficial uses, its transportation to the place of use, and its actual use.

wastewater reuse - The additional use of once-used water.

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2. American Public Health Association. 1981. Glossary - Water and Wastewater Control Engineering. 3rd Edition. American Public Health Association. Washington, D.C.
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APPENDIX I
HEAVY METAL CONTENTS OF SELECTED CALIFORNIA SOILS

Appendix I. Heavy metal contents of selected California soils[a]

Soil Series	pH	CEC (meq/100 g)	O.M. (%)	Cd	Cr	Cu	Ni	Pb	Zn	Fe	Mn	Reference[b]
				(μg/g)								
Holland	6.4	8.8	1.24	0.24	-	33.3	21.0	-	142	-	-	1
Ramona	5.2	4.4	0.43	<0.1	-	16.3	13.2	-	52.9	-	-	1
Helendale	7.5	5.4	0.25	<0.1	-	17.3	12.7	-	44.2	-	-	1
Baywood	4.9	4.5	0.30	0.5	32	4	29	-	11	11,375	144	2
Calhi	8.1	2.9	0.15	0.5	4	5	8	-	21	9,750	188	2
Delhi	7.5	4.7	0.55	0.6	11	11	13	-	40	19,000	275	2
Hanford	6.1	6.8	0.48	0.8	9	11	9	-	44	20,500	400	2
Milham	7.5	16.3	0.40	1.0	27	18	36	-	58	23,000	425	2
Redding	5.8	15.6	1.68	0.6	13	12	10	-	30	21,000	313	2
Greenfield	6.5	8.7	0.8	0.4	19	15	7	9	82	-	-	3
Domino	7.8	14.0	4.3	0.3	14	22	17	22	91	-	-	3
Ramona	6.5	-	-	0.5	10	14	11	13	53	-	-	3
Redding	5.0	9.8	0.44	0.2	-	9	5.6	11.3	5	8,564	113	4
Oakley	7.0	5.2	0.09	0.3	-	10	10.0	8.1	28	9,845	210	4
Holtville	7.7	27.3	0.61	1.1	-	20	21.0	26.9	57	17,690	193	4
Redding	4.8	9.8	2.6	<0.1	-	6.5	5.5	-	26	9,500	200	5
St. Miguel	5.0	17.7	3.3	<0.1	-	9.5	8.0	-	63	23,000	660	5
Hanford	5.3	7.6	0.9	<0.1	-	12	8.0	-	47	16,000	310	5
Altamont	5.7	37.9	3.0	<0.1	-	14.5	12.5	-	84	20,500	450	5
Domino	7.4	16.2	1.4	<0.1	-	29	24.5	-	112	39,000	740	5
Arizo	7.5	6.5	0.6	<0.1	-	14.5	9.5	-	87	10,000	500	5
Holtville	7.7	27.3	0.9	<0.1	-	20.5	21.5	-	78	16,000	450	5
Simona	7.8	7.4	0.7	<0.1	-	10.5	10.0	-	44	5,400	220	5
Lindsay	4.2	11.9	-	0.2	-	-	-	-	50	-	-	6
Omni	7.6	46.1	-	0.3	-	-	-	-	110	-	-	6
Sacramento	7.8	37.0	-	-	-	-	-	-	100	-	-	6
Mean				0.34	15.4	14.6	14.1	16.6	60.4	16,477	340	
Standard deviation				0.29	9.0	7.1	7.9	8.1	33.0	8,080	179	

a. All soils were extracted with 4 M HNO_3 extraction (5 g of soil with 30 ml of 4 M HNO_3 at 70°C for 24 hr., dilute to 50 ml with additional HNO_3, shake for 30 min. and then filter).

b. References:

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