IRRIGATION WITH RECLAIMED MUNICIPAL WASTEWATER
A Guidance Manual

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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 acknowledgement section of the Manual.

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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	Volume %
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]	-	-	-	22×10^6
Fecal coliform bacteria,[e] MPN/100 mL	-	-	-	8×10^6
Viruses, PFU/100 mL[g,h]	-	-	-	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	Los Angeles County[b] Long Beach	Los Angeles County[b] Los Coyotes	Los Angeles County[b] 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.

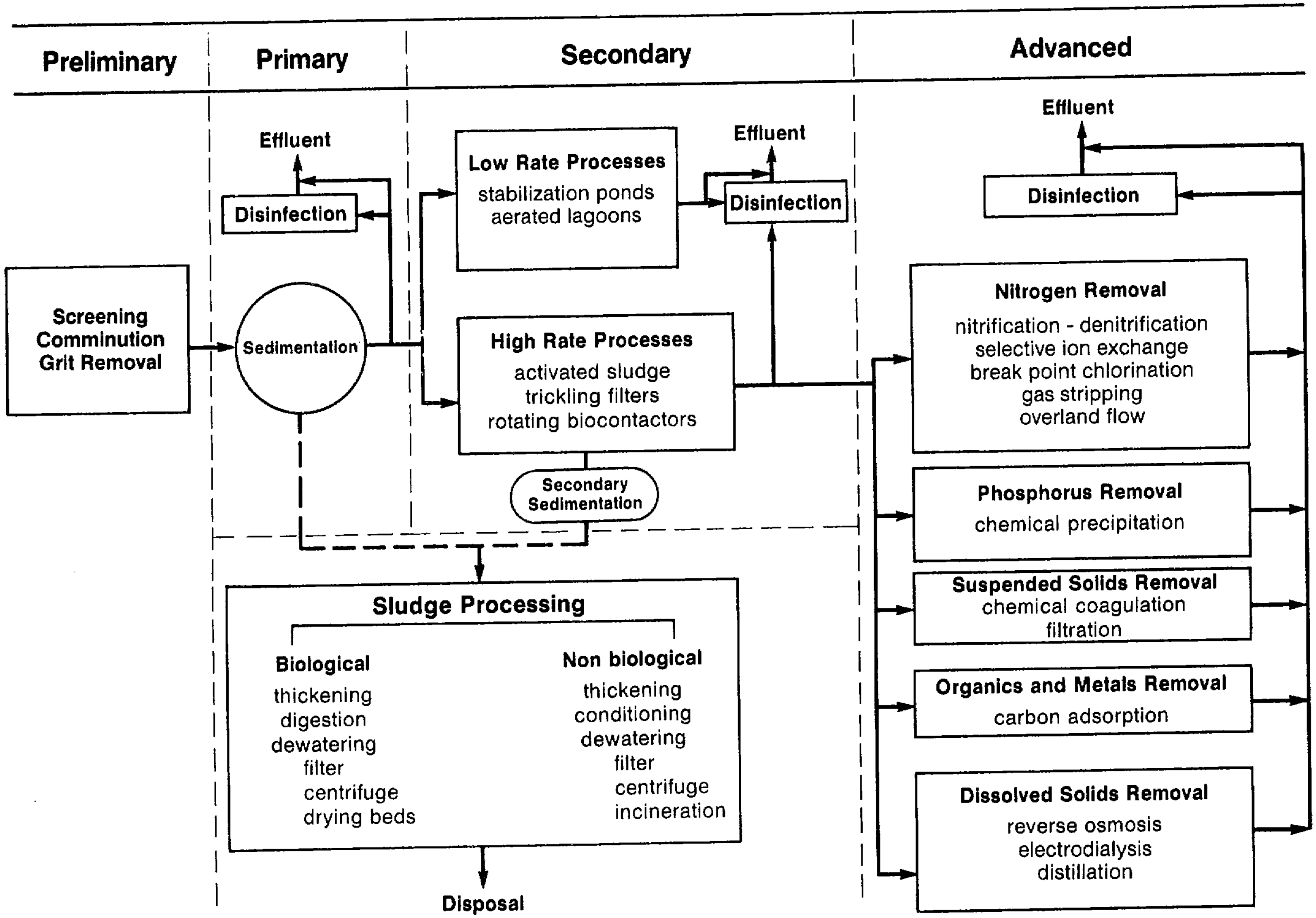

Figure 2-1. Generalized flow sheet for wastewater treatment.

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.

High-Rate Biological Processes

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	Plant location			
	Trickling filter	Activated sludge		
	Chino Basin MWD (No.1)[b]	Chino Basin MWD (No.2)[b]	Santa Rosa Laguna[c]	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 10-5, p. 10-21.

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
Salinity			
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
Miscellaneous			
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 (*Melitotu:*)
- 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 gemmifera*)

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].

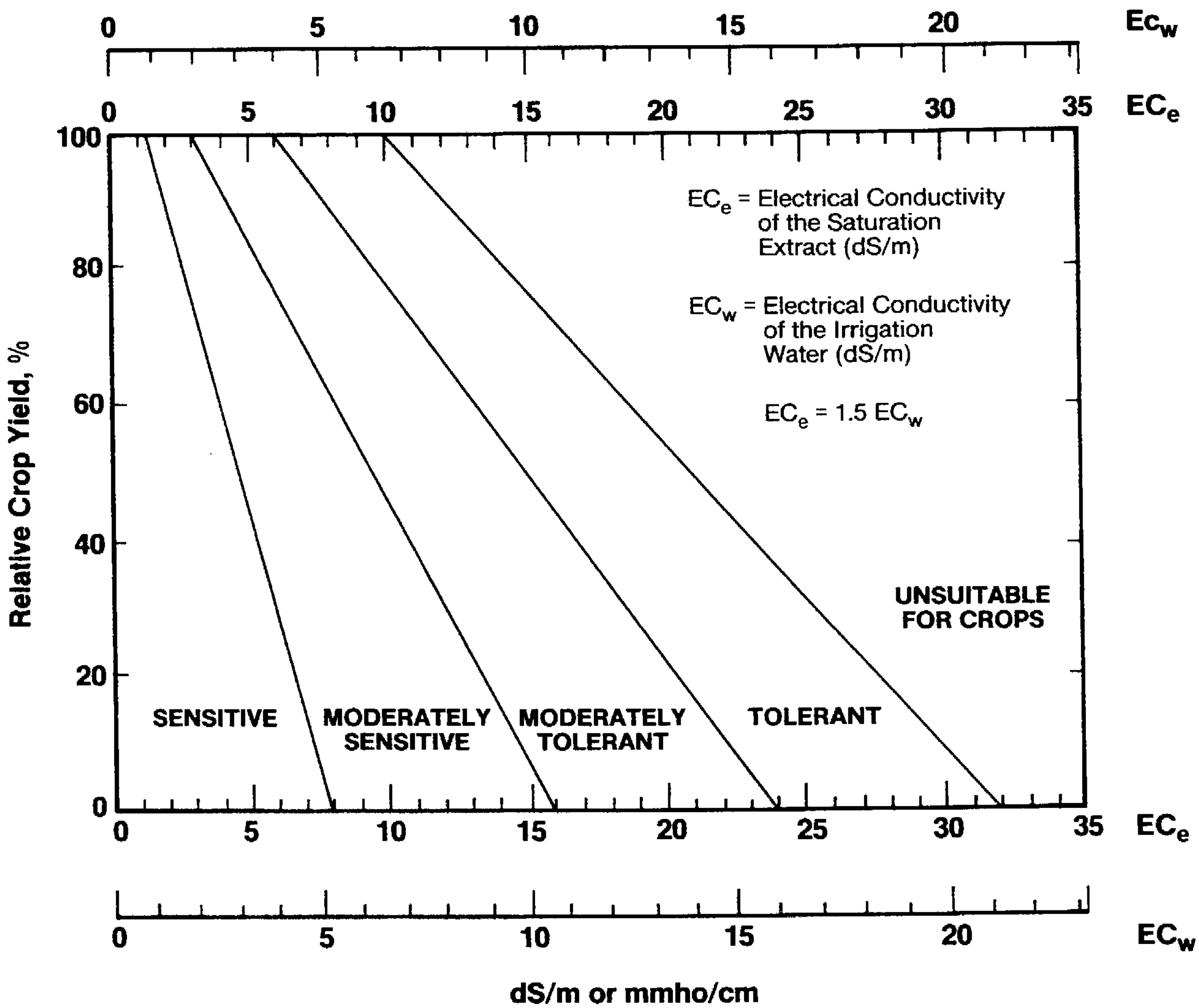

Figure 3-1. Divisions for relative salt tolerance rating of agricultural crops [13].

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*)

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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.

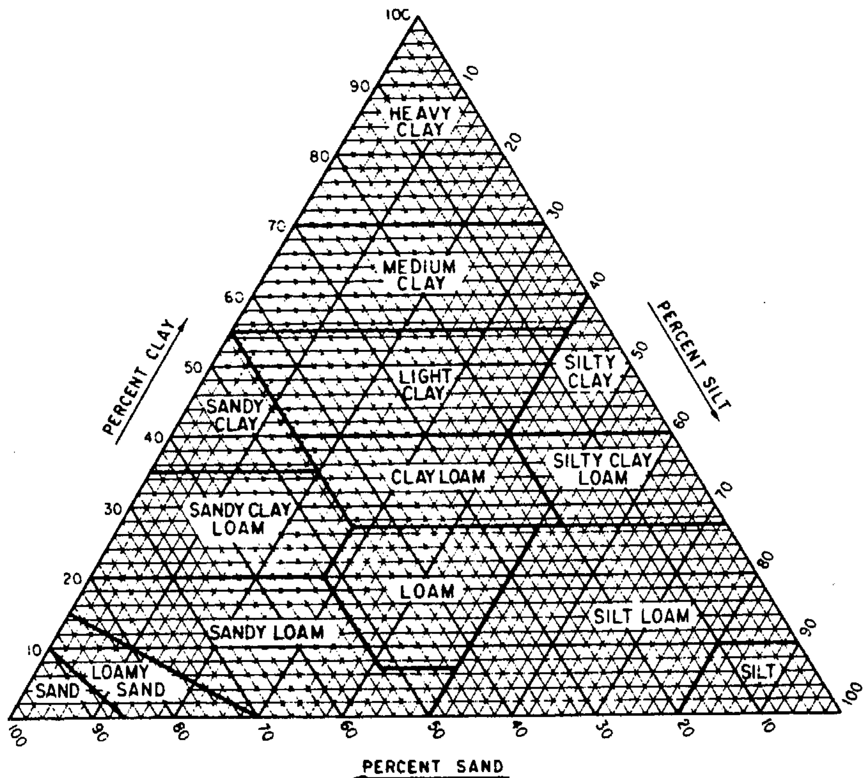
Soils of one series can differ in texture of the surface horizon or in the underlying substratum and in slope, erosion, stoniness, salinity, or other characteristics. On the basis of such differences, a soil series is divided into phases. The name of the soil phase or type commonly indicates a feature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

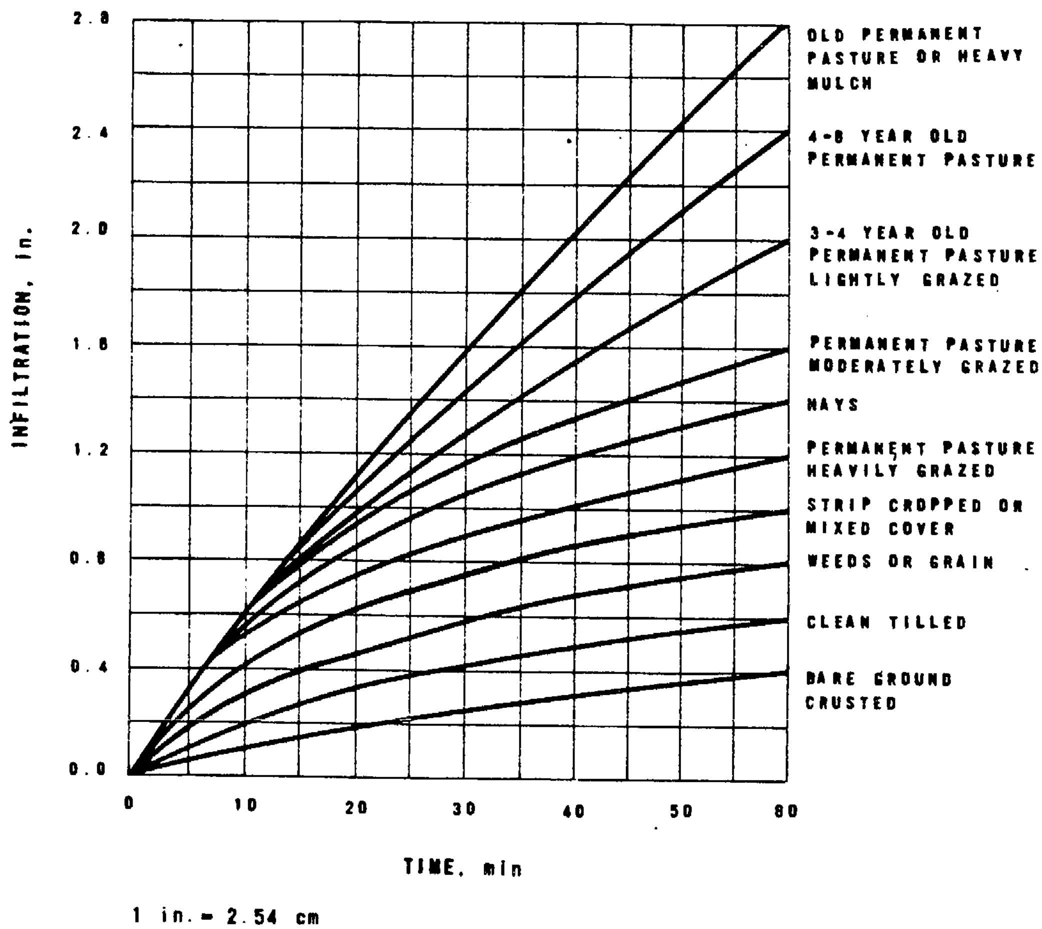


Figure 4-2. Infiltration rates for various crops [7].

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

W. O. Pruitt and R. L. Snyder

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_o) 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_o (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_o as obtained by interpolation from Plate No. 1 in DWR Bulletin 113-3 [7]. The term E_o 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_o 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_o estimates. ET_o 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_o. 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 microfiche 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 Humid-Dry-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

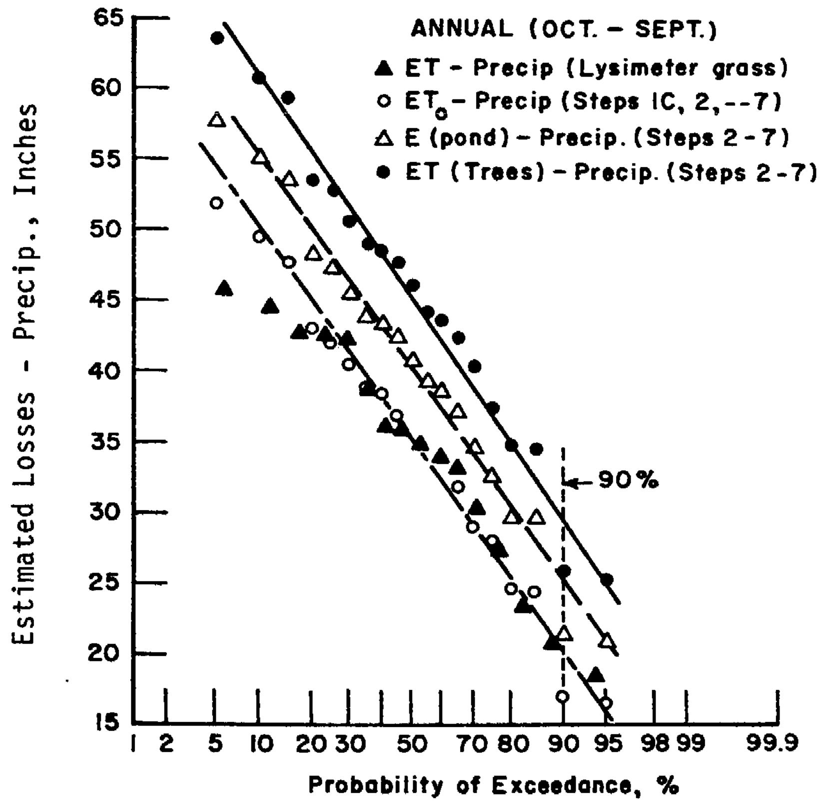

Figure 5-1. Frequency distribution analysis of data from Table 5-3b in Example 5-1 for ET_0, ET(trees), and E(pond), all minus precipitation. Yearly totals for hydrologic years (Oct.-Sept.), Davis, Calif. An analysis of measured ET(grass) - P (not tabulated in Table 5-3b) is shown for comparison with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

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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).

<u>Step 1</u>. 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. <u>Step 2</u> – 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. <u>Steps 3-4</u> – 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. <u>Step 5</u> – Precipitation data summed for Nov.-Mar. from microfiche frames of DWR Bull. California rainfall summary [14].

d. <u>Step 6</u> – Subtract precipitation from ET_o and ET(trees).

e. <u>Step 7</u> – Distribution analysis.

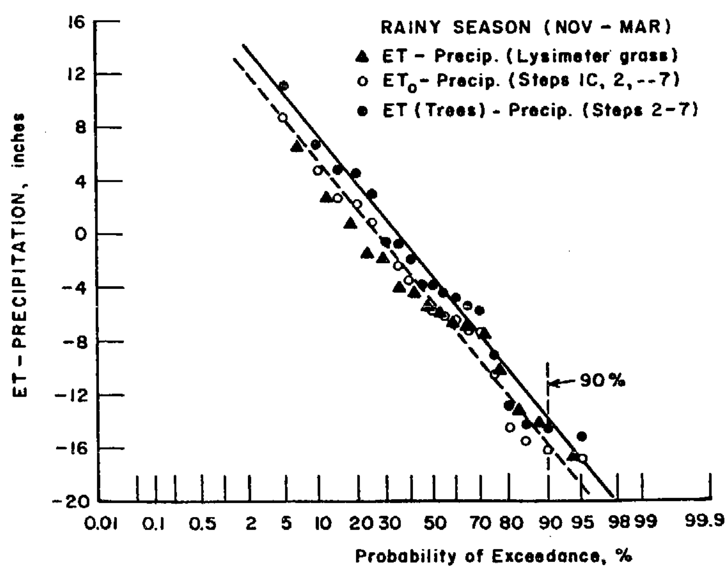

Figure 5-2. Frequency distribution analysis for ET_o - P and ET(trees) - P. An analysis of measured ET(grass) - P is shown for comparison. Davis, California. Rainy Season (November through March).

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.

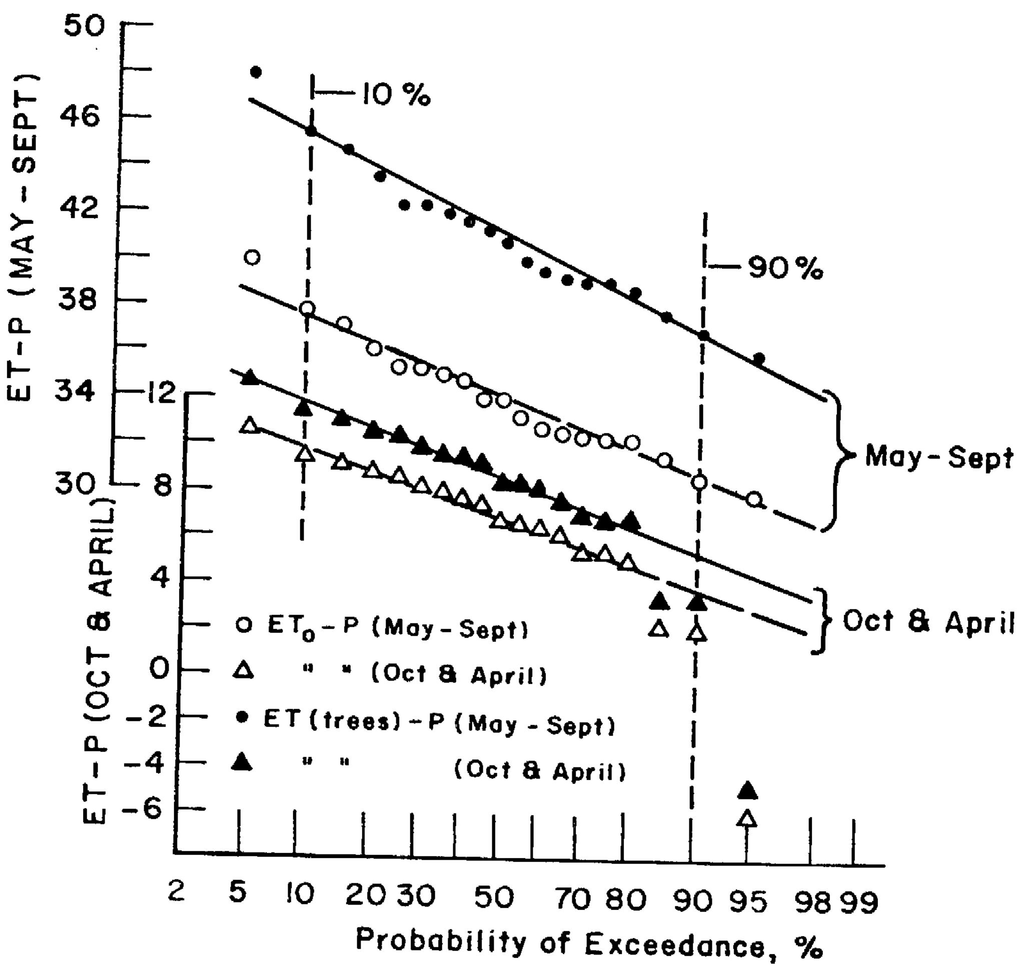

Figure 5-3. Frequency distribution analysis for ET_0 - P and ET(trees) - P for dry season (May-Sept.) and transition months (Oct. and Apr.) at Davis, Calif.

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.

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

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

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)

Example 5-3: Continued

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).

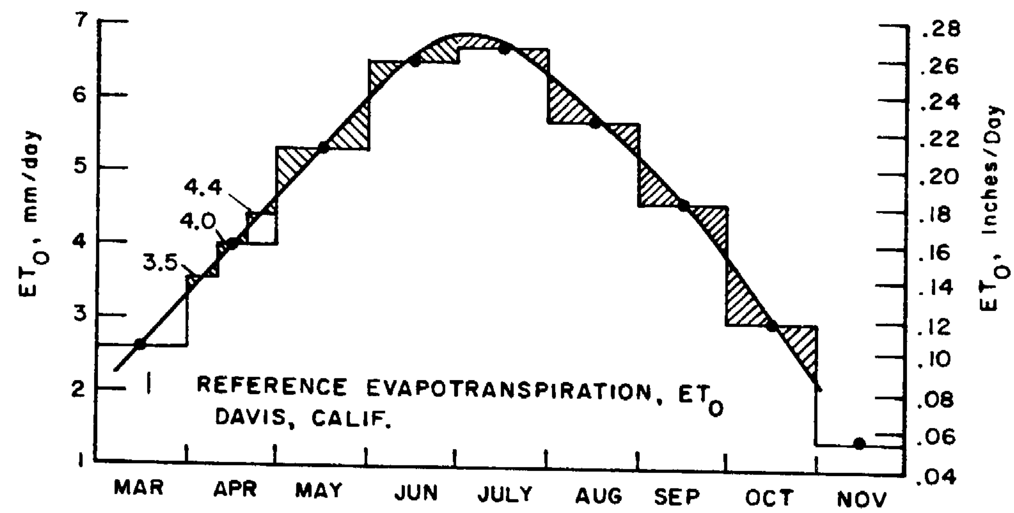

Figure 5-4. Plot of normal-year ET_o, and development of smooth curve (example for Davis).

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.

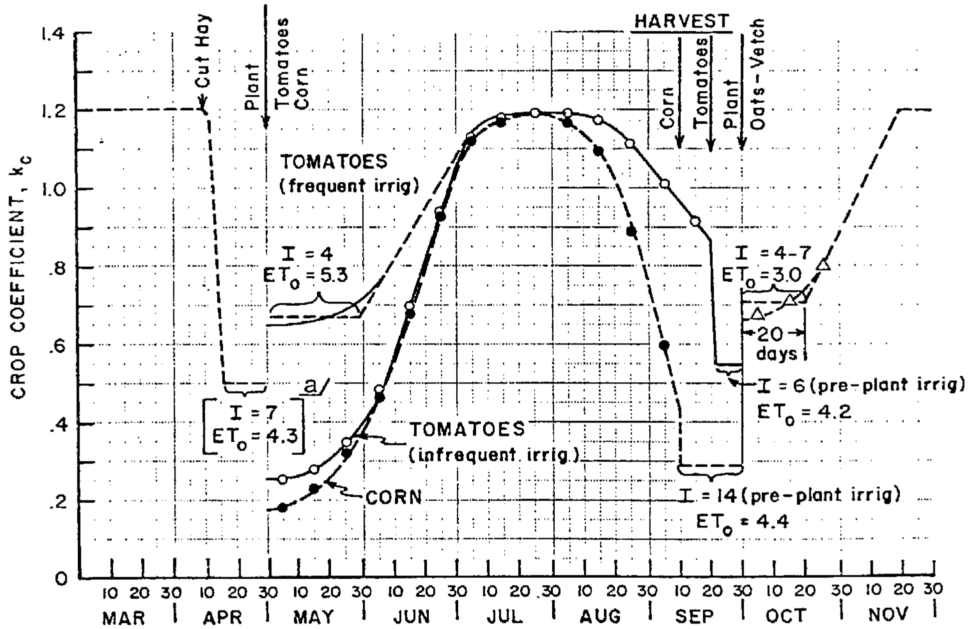

Figure 5-5. Development of crop coefficients for cropping sequences involving a Fall-Winter hay crop of oat and vetch with spring plantings of corn and tomatoes. Both frequent and infrequent early irrigation of tomatoes are illustrated.

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/	Oats - Tomatoes - Oats ET Inch e/	Oats - Tomatoes - Oats k_c b/,d/	Oats - Tomatoes - Oats 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.

Example 5-4: Continued

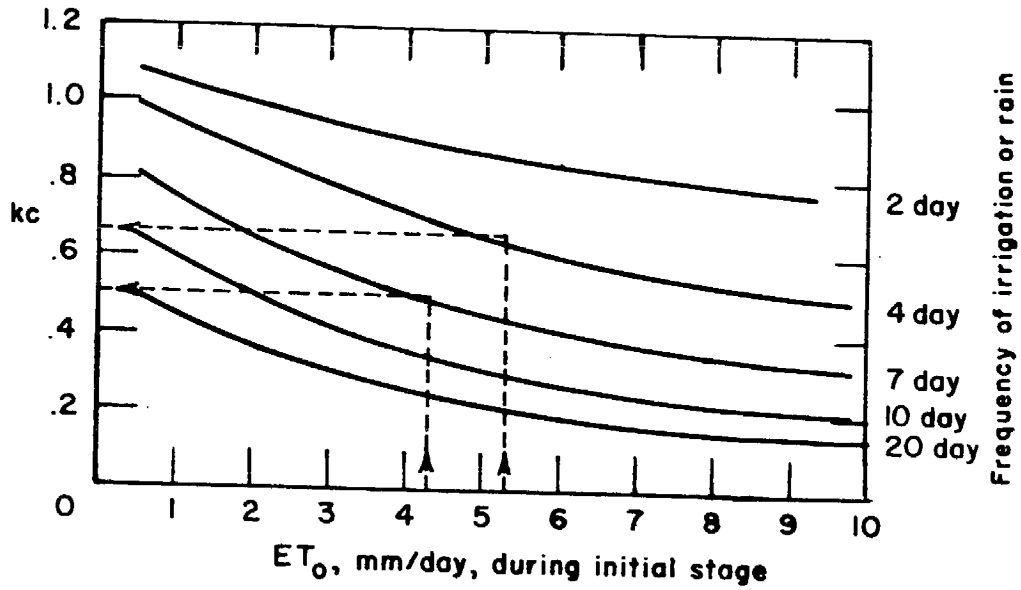

Figure 5-6. Average K_c value for Initial Development Stage as related to level of ET_o and the frequency of irrigation and/or significant rainfall (Adapted from Doorenbos and Pruitt [3]).

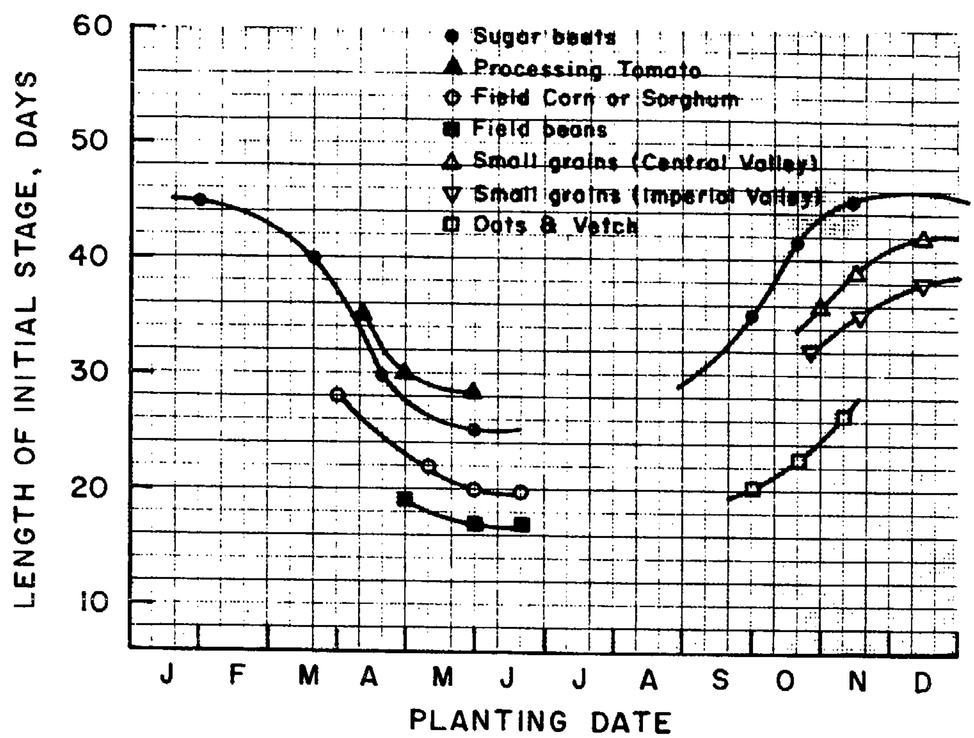

Figure 5-7. Length in days of Initial Development Stage for several annual crops in California as a function of planting date.

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.

	Normal Year				Normal Year		Adj. Factor	90% Probability	
	ET_o	ET (Oats, Tomato, Oats)	ET (Oats, Corn, Oats)	P	ET - P (Oats, Tomato, Oats)	ET - P (Oats, Corn, Oats)	"C" for 90% prob.	$(ET - P)_{0.9}$ (Oats, Tomato, Oats)	$(ET - P)_{0.9}$ (Oats, Corn, Oats)
Month	Inch[a]	Inch[b]	Inch[b]	Inch	Inch	Inch	c	Inch	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_0 were derived by normalizing E_0 data for a two-year occurrence frequency against the normal-year July ET_0 as obtained from the ET_0 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_0 for the peak demand month, will provide peak ET_0 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.	RAW or MAD[a] at peak-demand period mm	Ratio, Fig. 5-8 b	Normal-Year[c] July mean monthly ET mm/day	Normal-Year[c] July mean monthly ET 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.

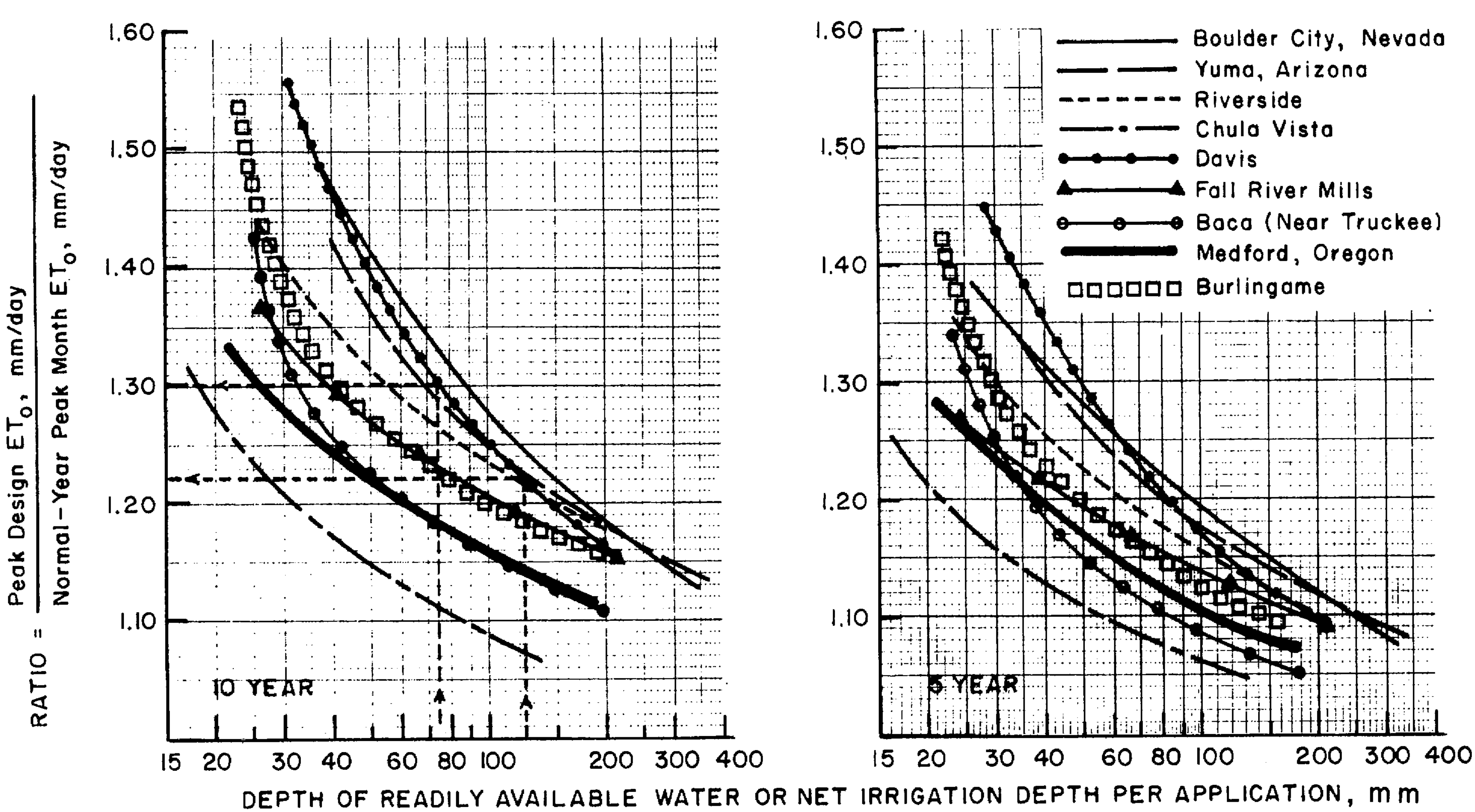

Figure 5-8. Examples for California and bordering state locations of the ratio of design peak ET_o to normal-year ET_o (July) as a function of readily available soil water or net irrigation application based on analyses of Bassett and Jensen [11].

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					

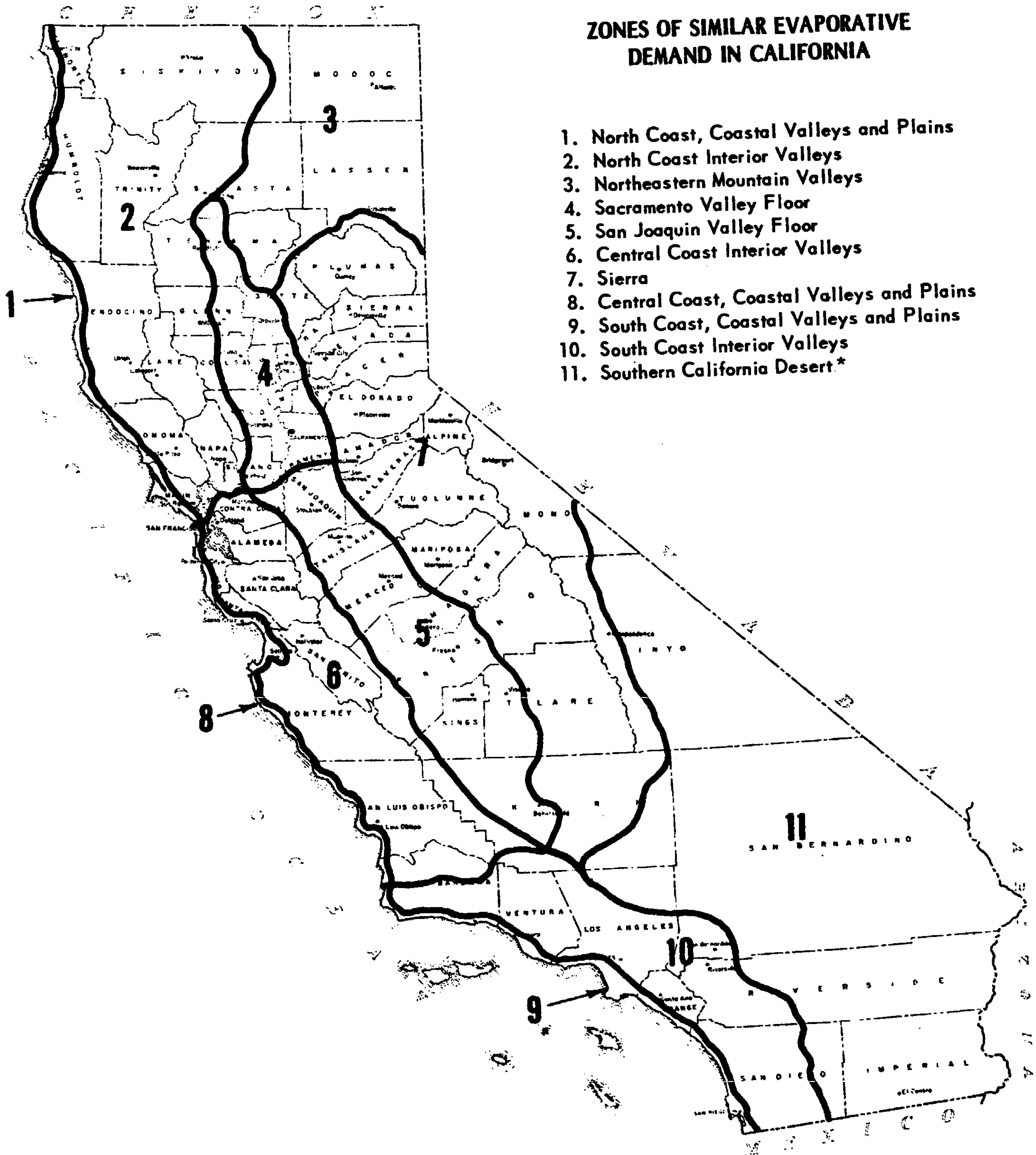

Figure 5-9. Zones of similar evaporative demand. After California DWR Bull. 113-3 [7].

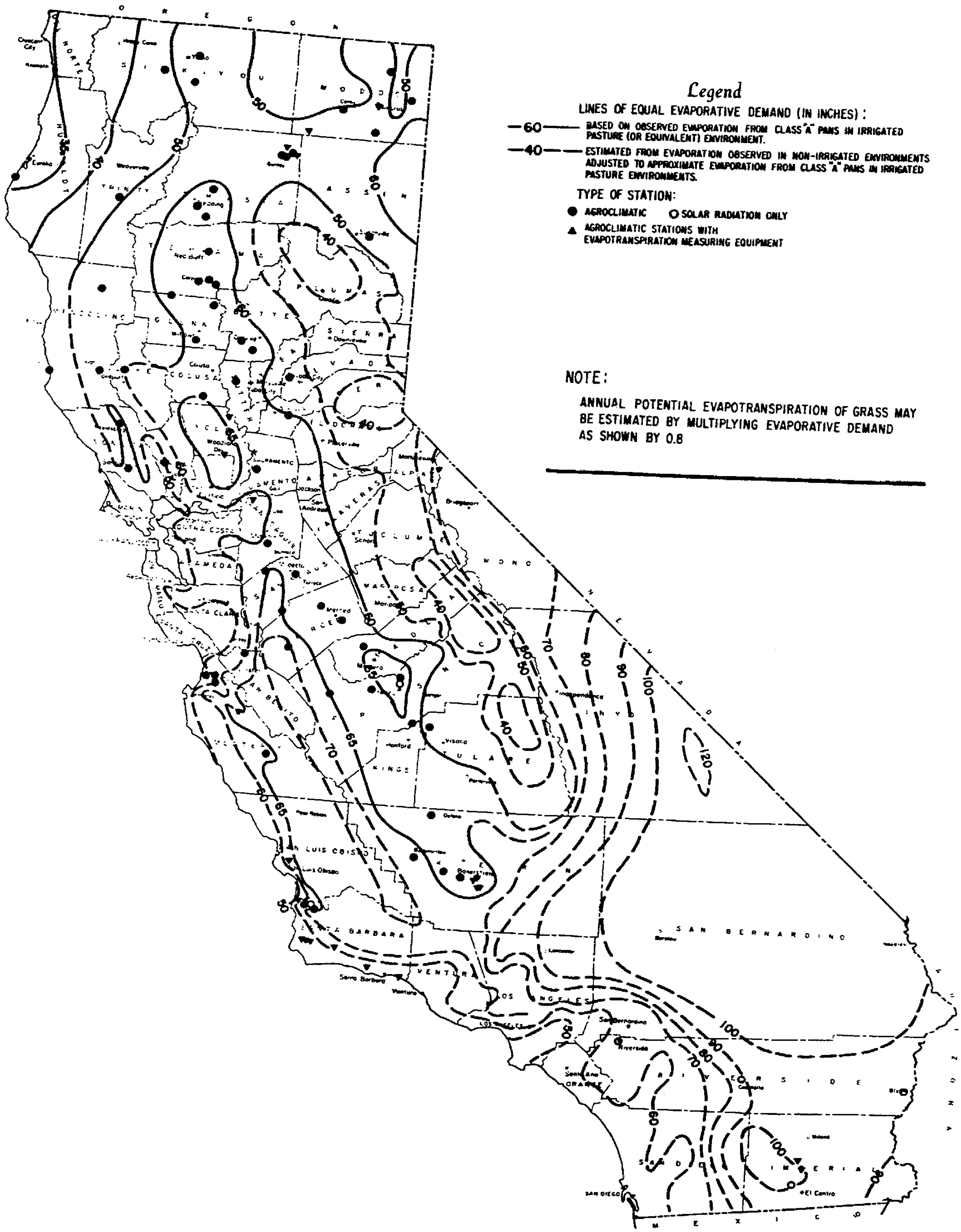

Figure 5-10. Annual evaporative demand in California, the expected evaporation loss in inches (for normal conditions) from a National Weather Service Class "A" pan located in an irrigated pasture (or comparable environment). After California DWR Bull. 113-3 [7].

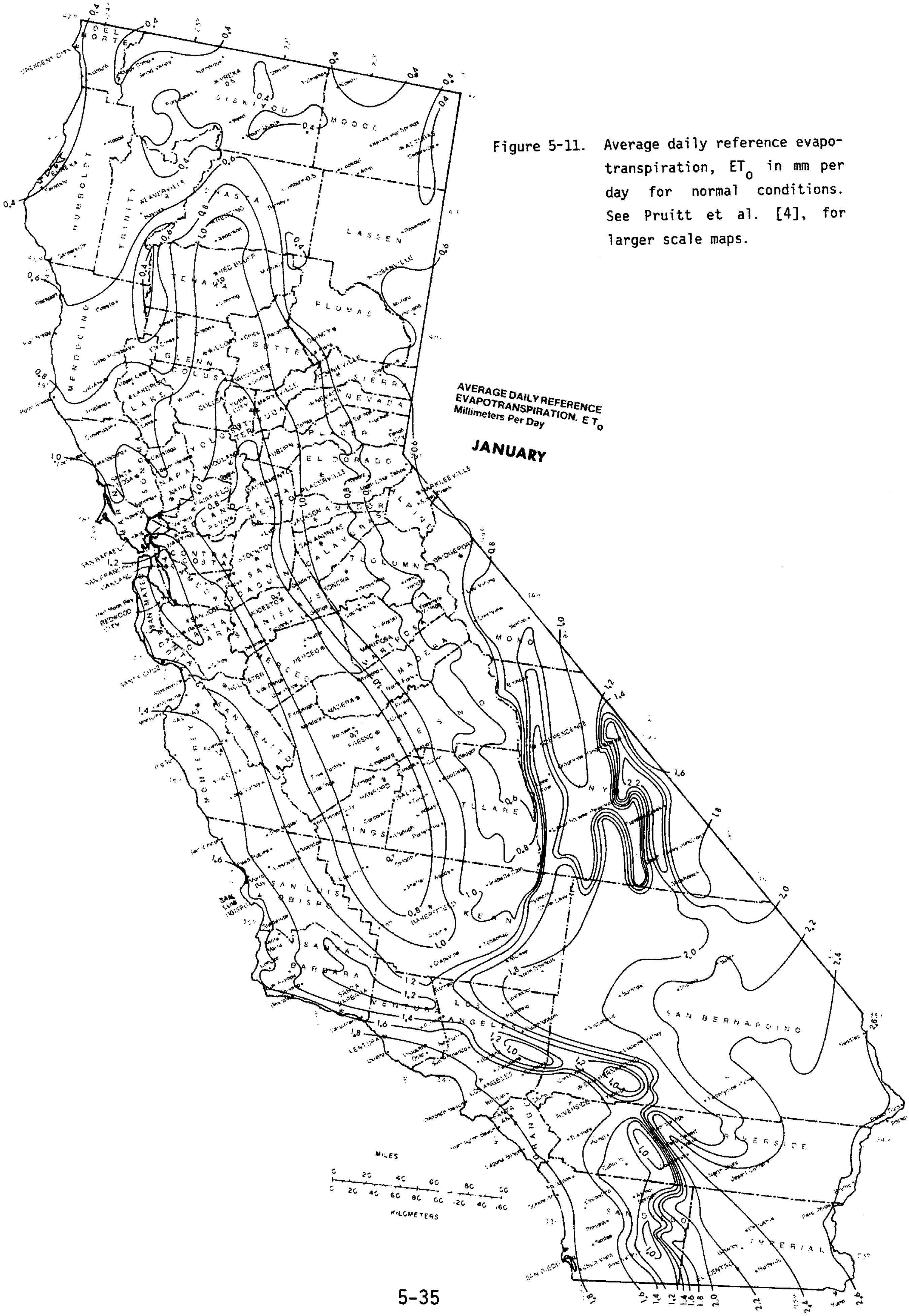

Figure 5-11. Average daily reference evapotranspiration, ET_0 in mm per day for normal conditions. See Pruitt et al. [4], for larger scale maps.

Figure 5-11. (Continued)

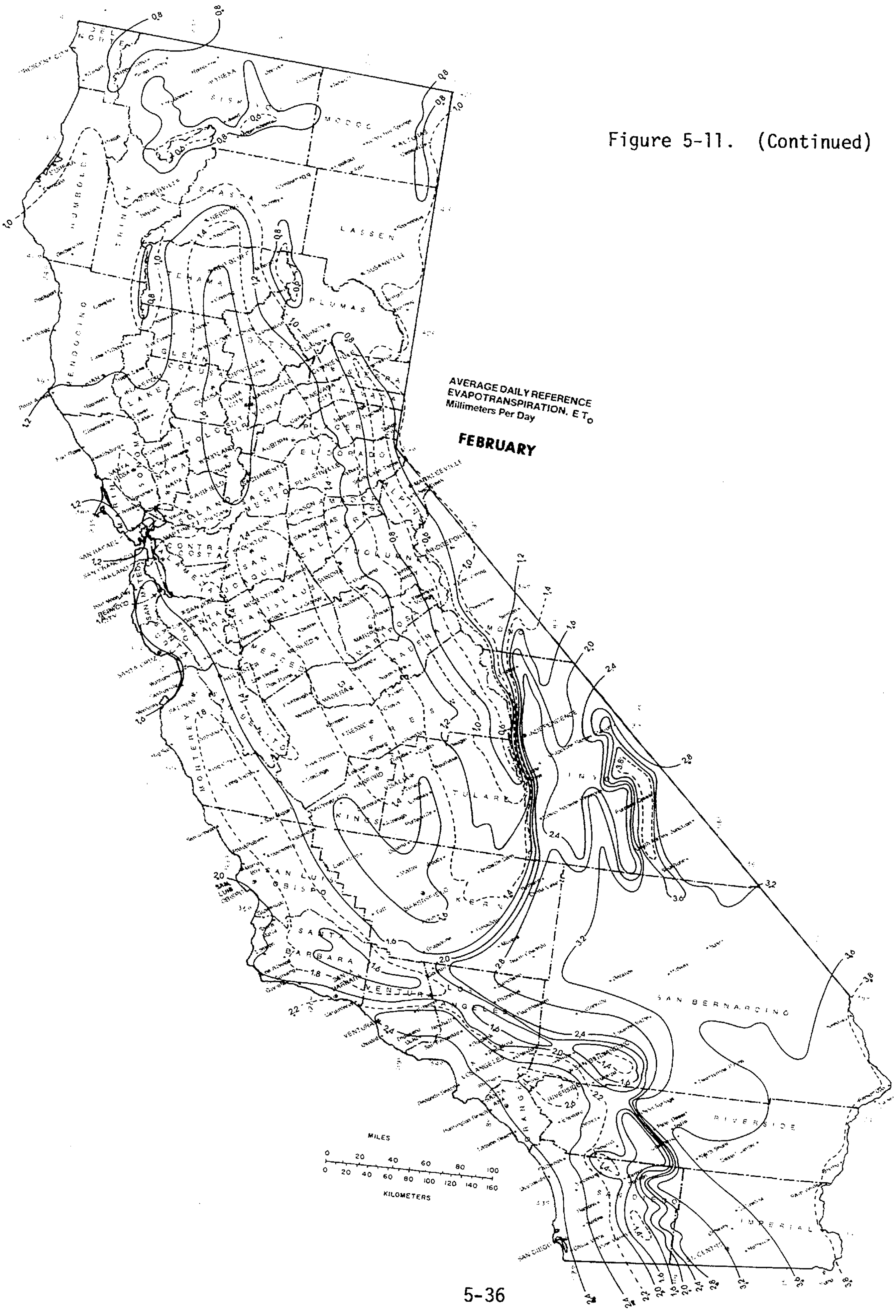

Figure 5-11. (Continued)

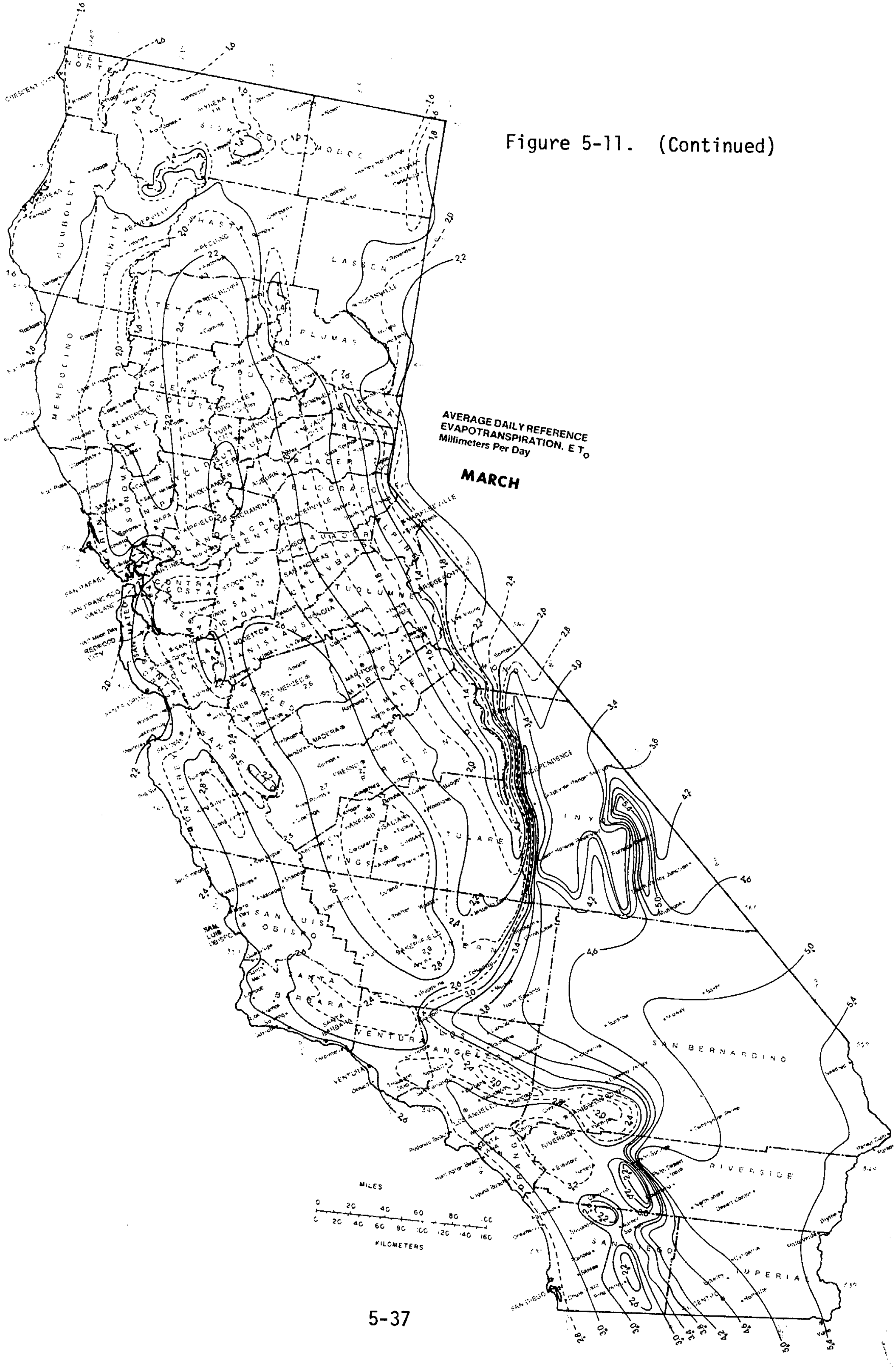

Figure 5-11. (Continued)

Figure 5-11 (Continued)

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Figure 5-11 (Continued)

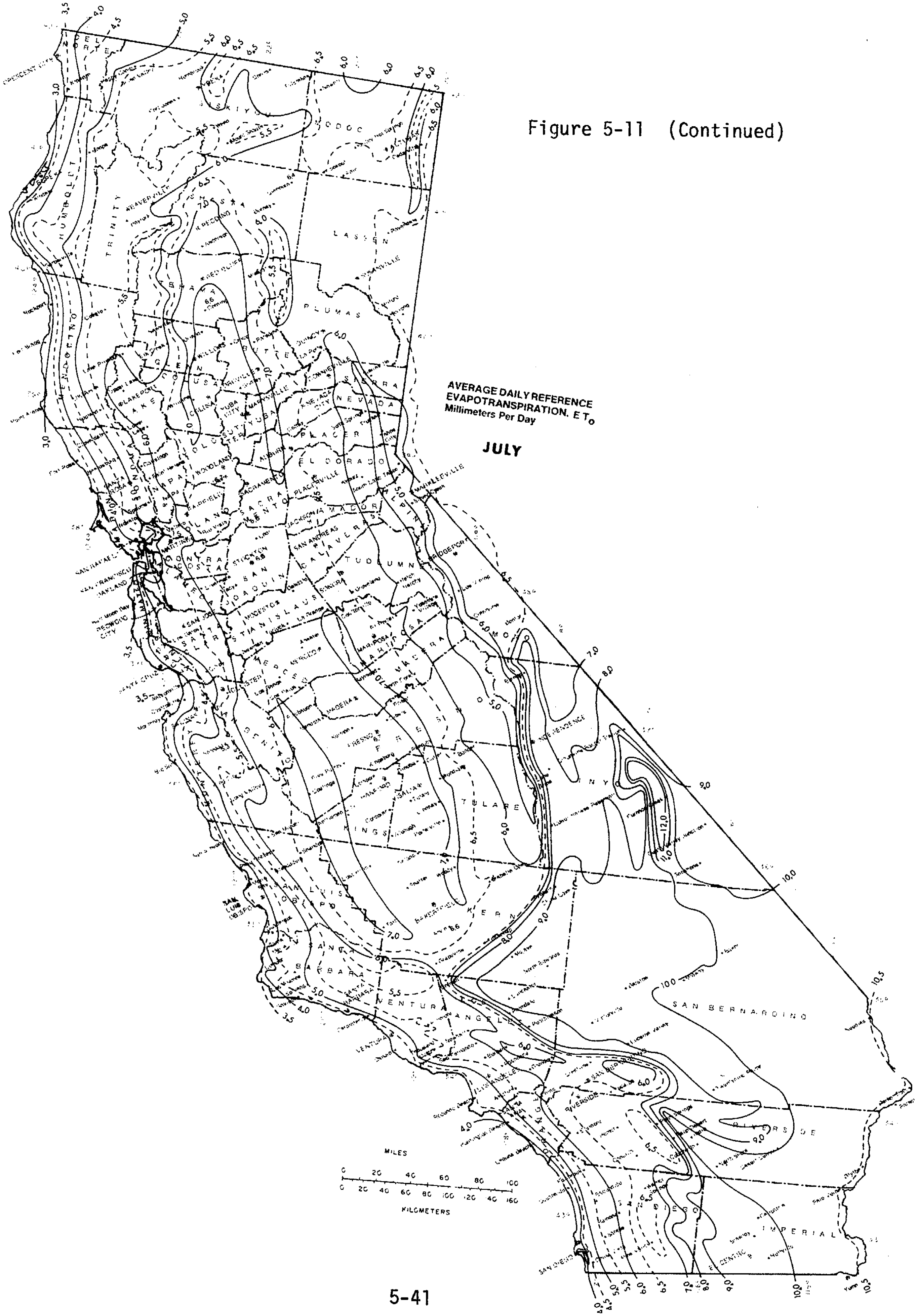


Figure 5-11. (Continued)

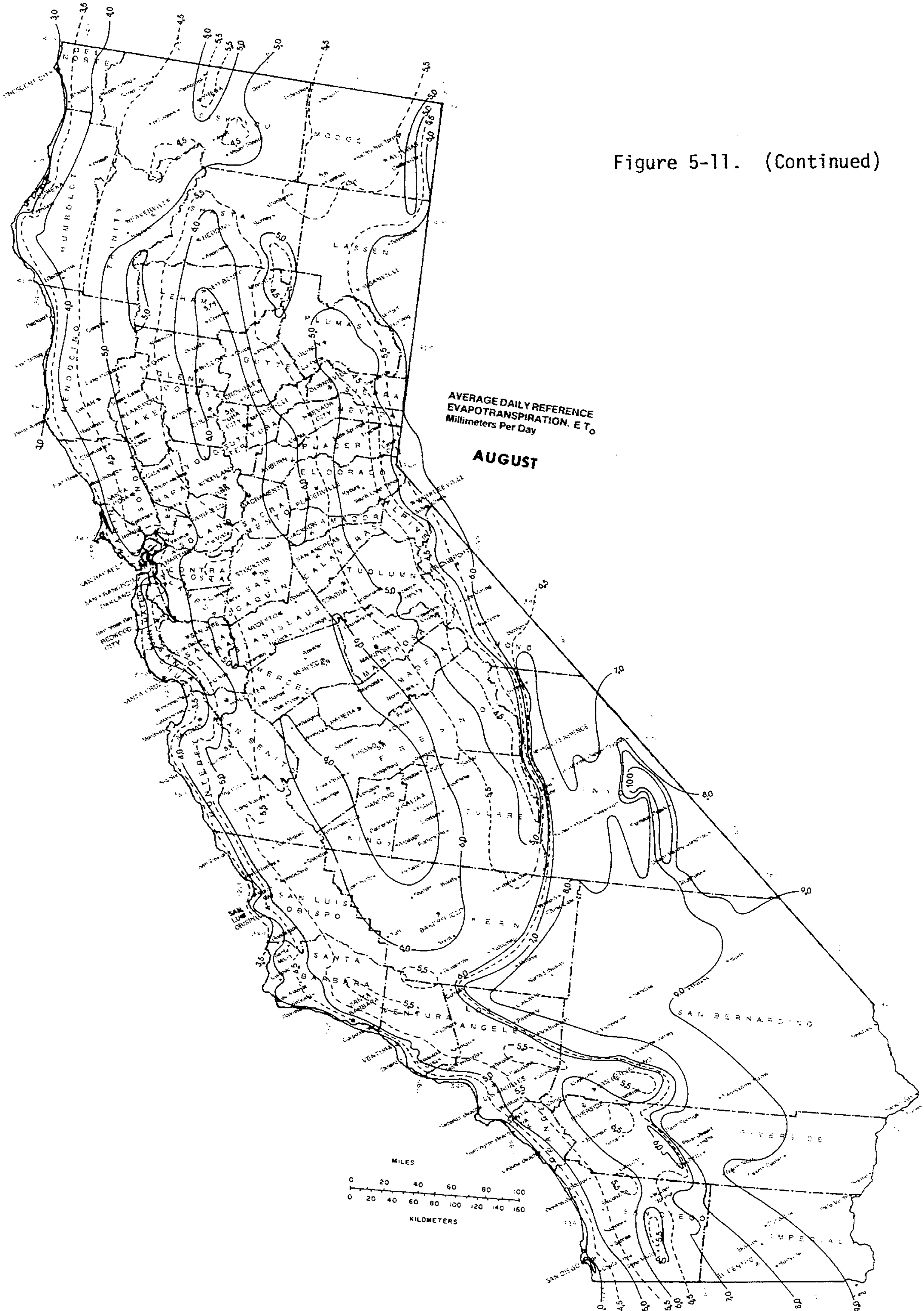


Figure 5-11 (Continued)

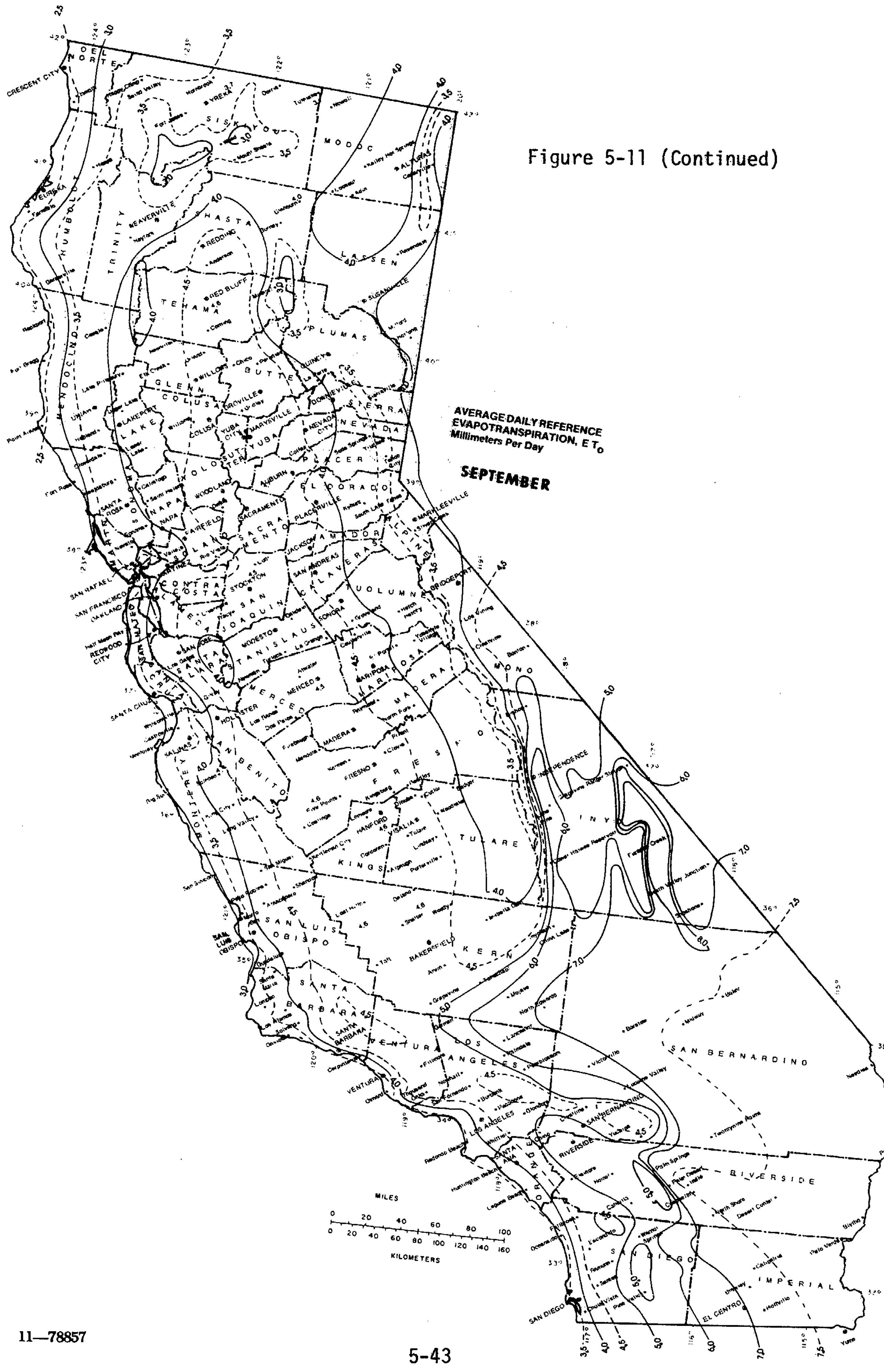


Figure 5-11 (Continued)

Figure 5-11 (Continued)

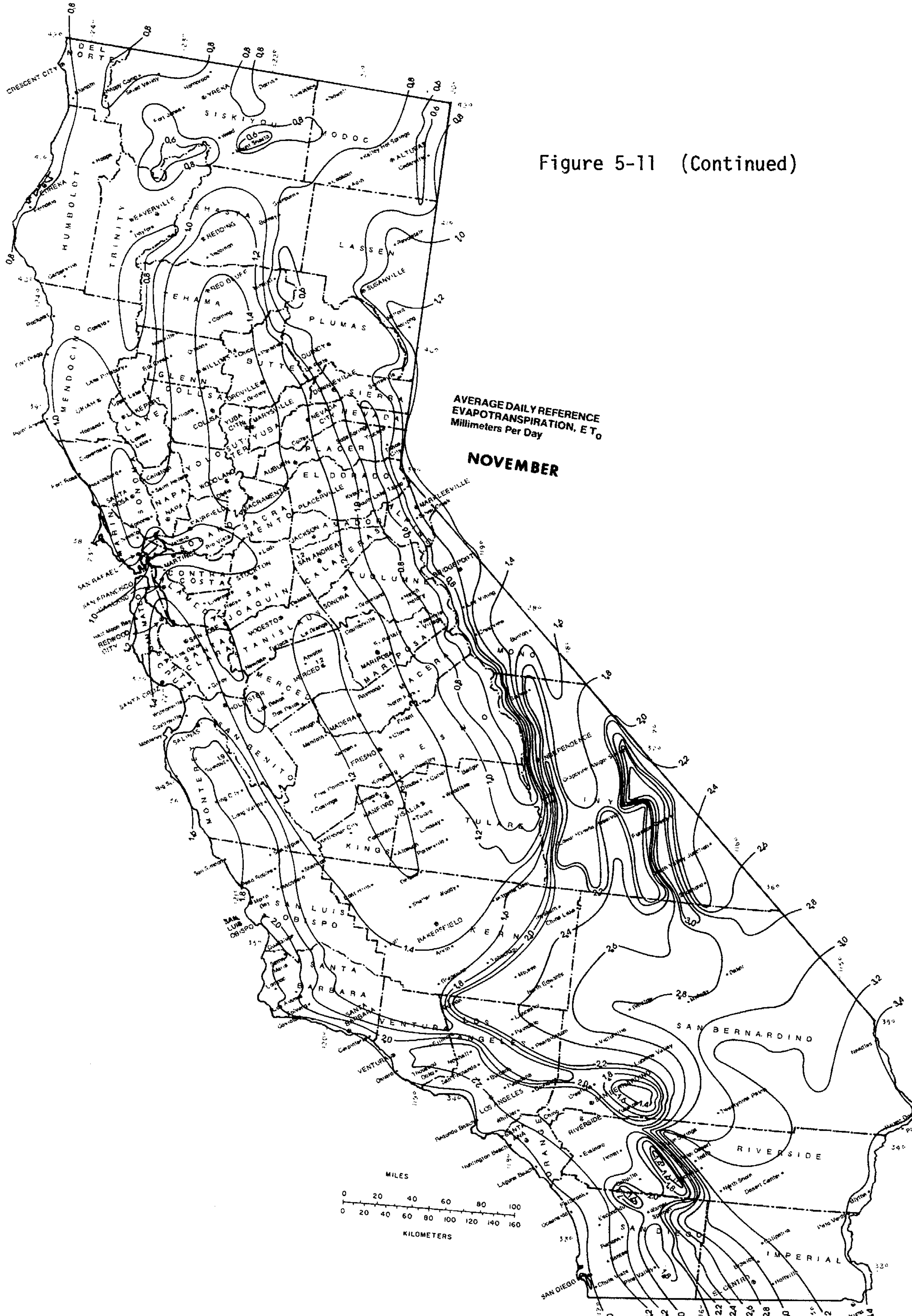
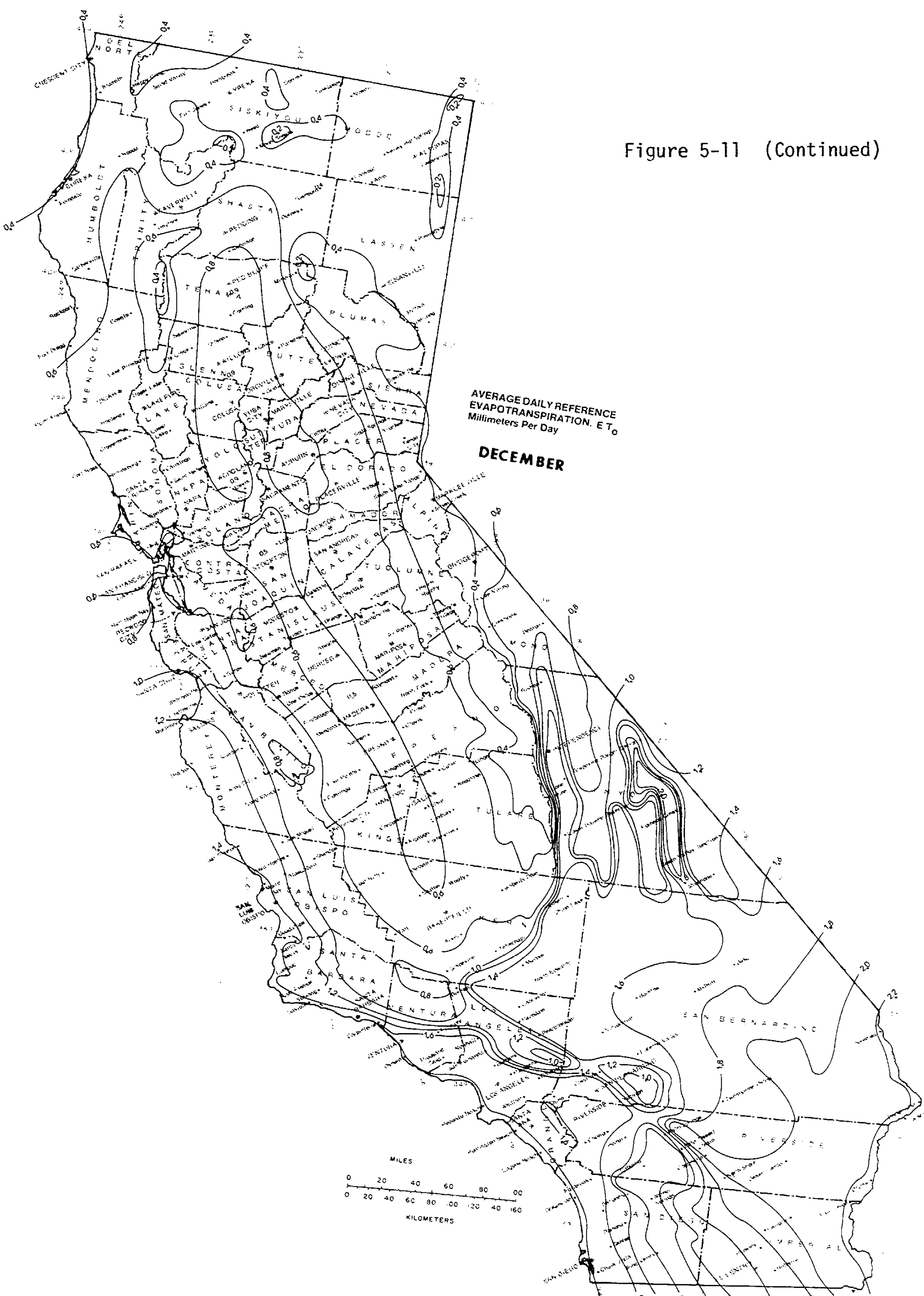


Figure 5-11 (Continued)



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CHAPTER 6

CROP SELECTION AND MANAGEMENT

M. R. George, G. S. Pettygrove, and W. B. Davis

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 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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