CHAPTER 7

WATER MANAGEMENT FOR SALINITY AND SODICITY CONTROL

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INTRODUCTION

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

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

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

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

HOW SALT AFFECTS PLANTS

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

Osmotic Effects

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

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

Specific Ion Toxicity

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

Boron

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

Chloride

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

Bicarbonate

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

Sodium

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

Poor Soil Physical Conditions

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

HOW SALINITY AND SODICITY ARE MEASURED

Water

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

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

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

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

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

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

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

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

Chemical laboratory reports often include two sodium adsorption ratios:

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

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

Soil

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

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

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

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

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

WATER MANAGEMENT FOR SALT CONTROL

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

Basic Aspects

Soil Salinity

Salts are added to the soil in the irrigation water. For example, an acre-foot (1233 m^3) of relatively low salinity irrigation water with an EC of 0.5 dS/m (~320 mg/L) contains 0.43 tons (390 kg) of salt. When water is taken up by plants or evaporates from the soil surface, most of the salt is left behind in the soil. Salt contents of 3 to 4% have been reported [8] for alfalfa grown under saline conditions. At 4%, an annual alfalfa yield of 10 tons/acre (22 Mg/ha) would remove about 0.4 tons/acre (0.9 Mg/ha) of salt. If five acre-ft (1500 mm) of water with an EC of 0.5 dS/m were used to grow the crop, the salt applied per acre would be 2.2 tons (2 Mg). Salt uptake by the crop would be less than 10% of that applied. Consequently, repeated irrigation without moving the salts to depths below the root zone (leaching) results in salt accumulation in the root zone. The saltier the water, the faster the accumulation.

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

Crop Response

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

Leaching Requirement

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

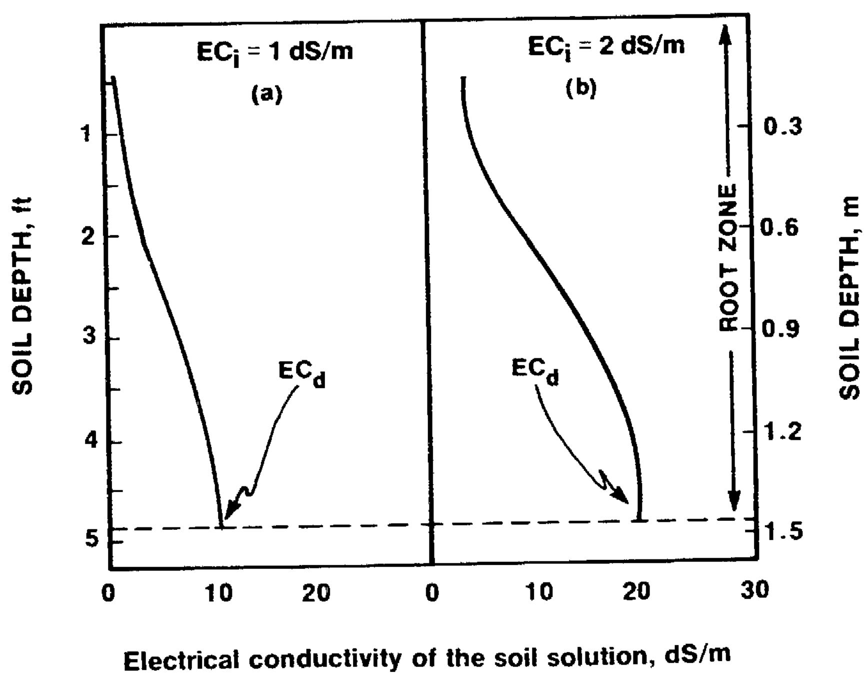

Figure 7-1. The electrical conductivity (EC) of the soil solution through the root zone for two irrigation water (EC=1 and 2 dS/m) and one leaching fraction (=0.1, or 10%).

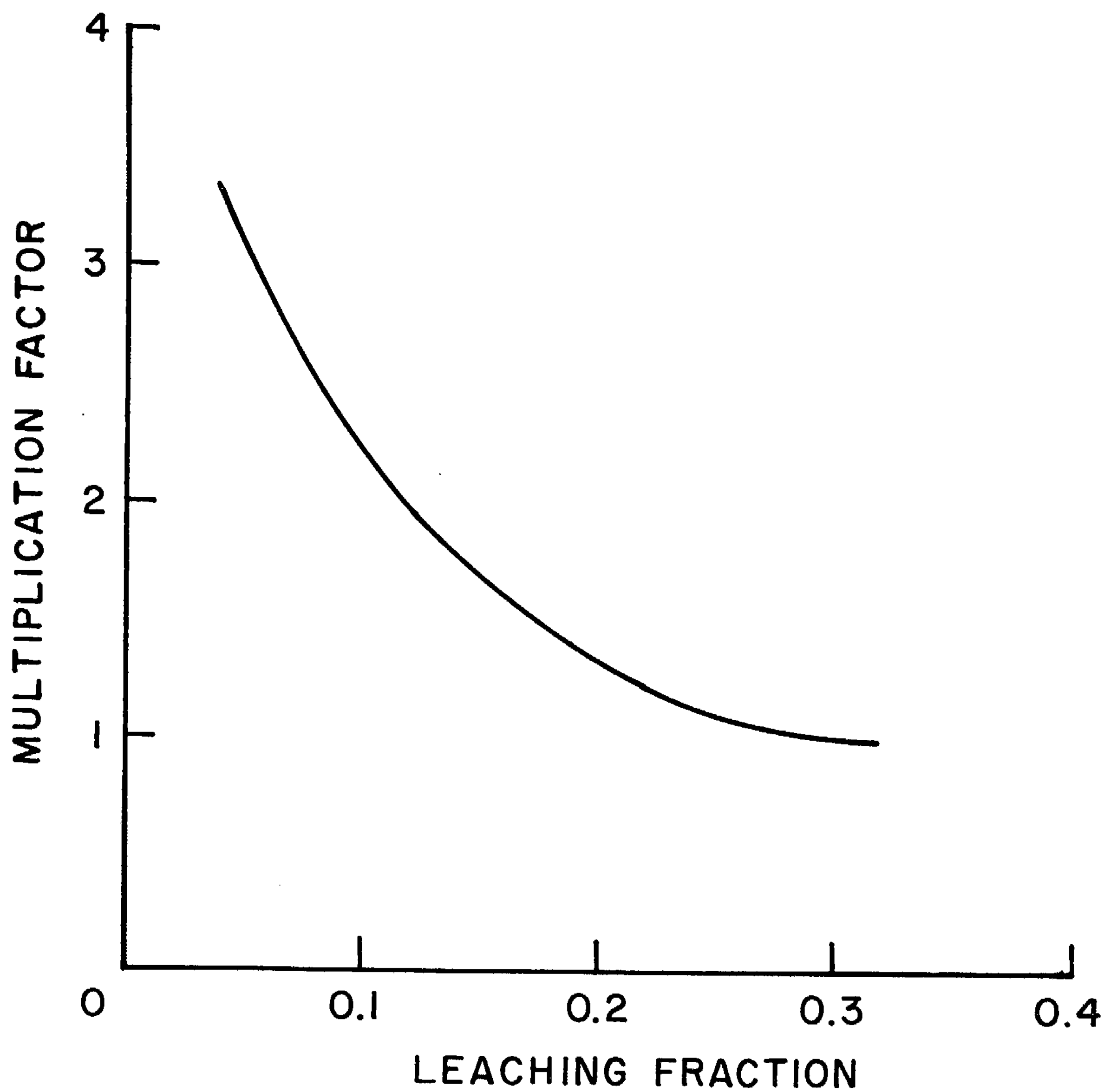

Figure 7-2. Multiplication factor used to interconvert leaching fraction and the ratio of threshold salinity to irrigation water salinity.

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

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

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

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

Some Practical Considerations

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

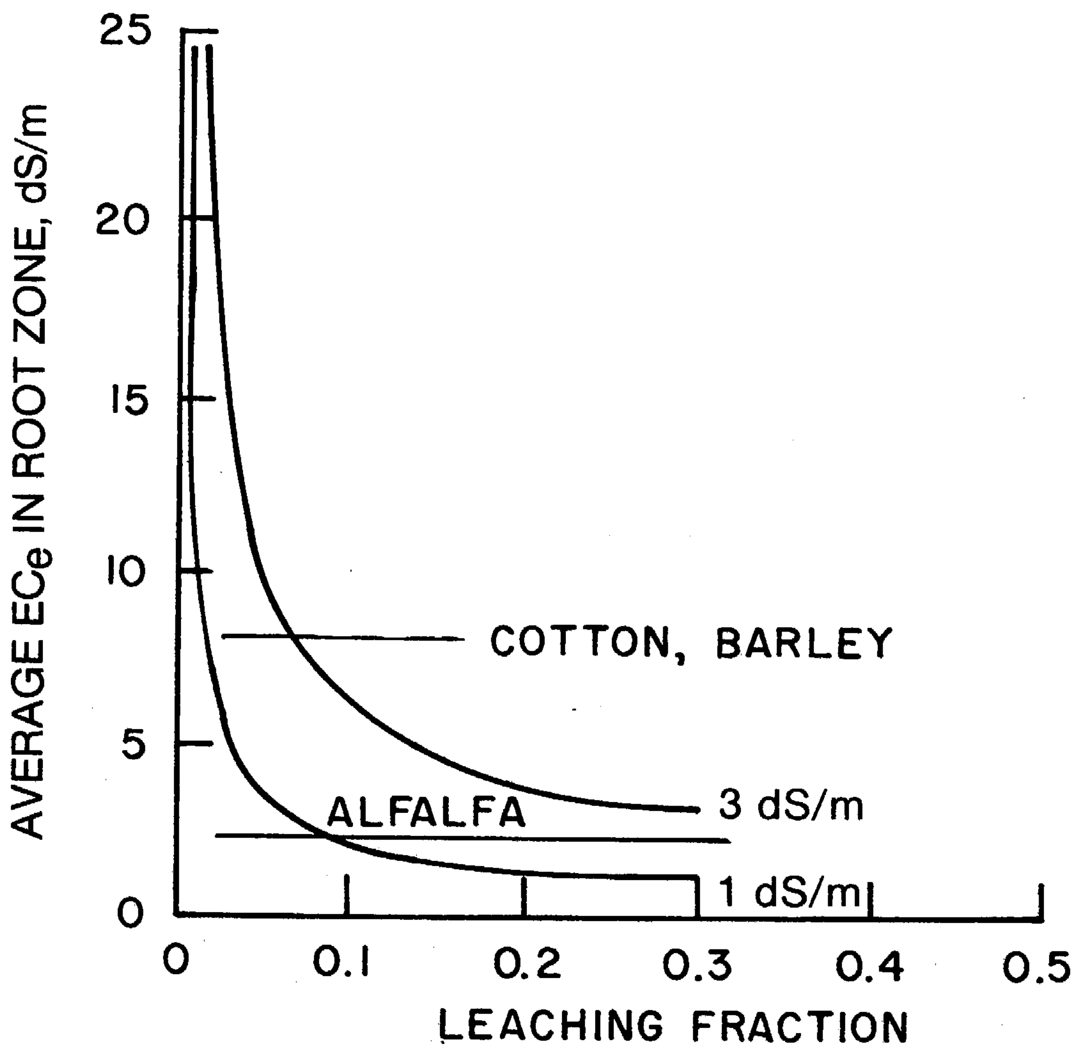

Figure 7-3. Relationship of irrigation water salinity, root zone salinity and leaching fraction.

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

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

RECLAMATION OF SALINE SOILS WITH TREATED WASTEWATER

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

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

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

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

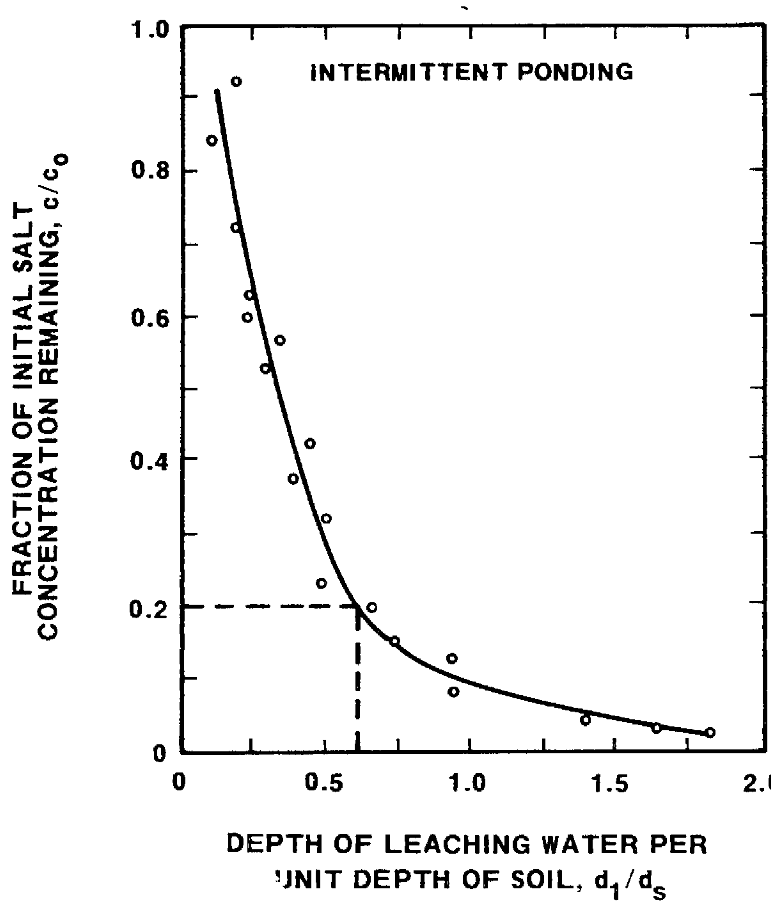

Figure 7-4. Depth of leaching water (d_1) per unit depth of soil (d_s) required to reclaim a saline soil by ponding water intermittently.

IRRIGATION WITH HIGH-SODIUM/LOW-SALINITY WATERS

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

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

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

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

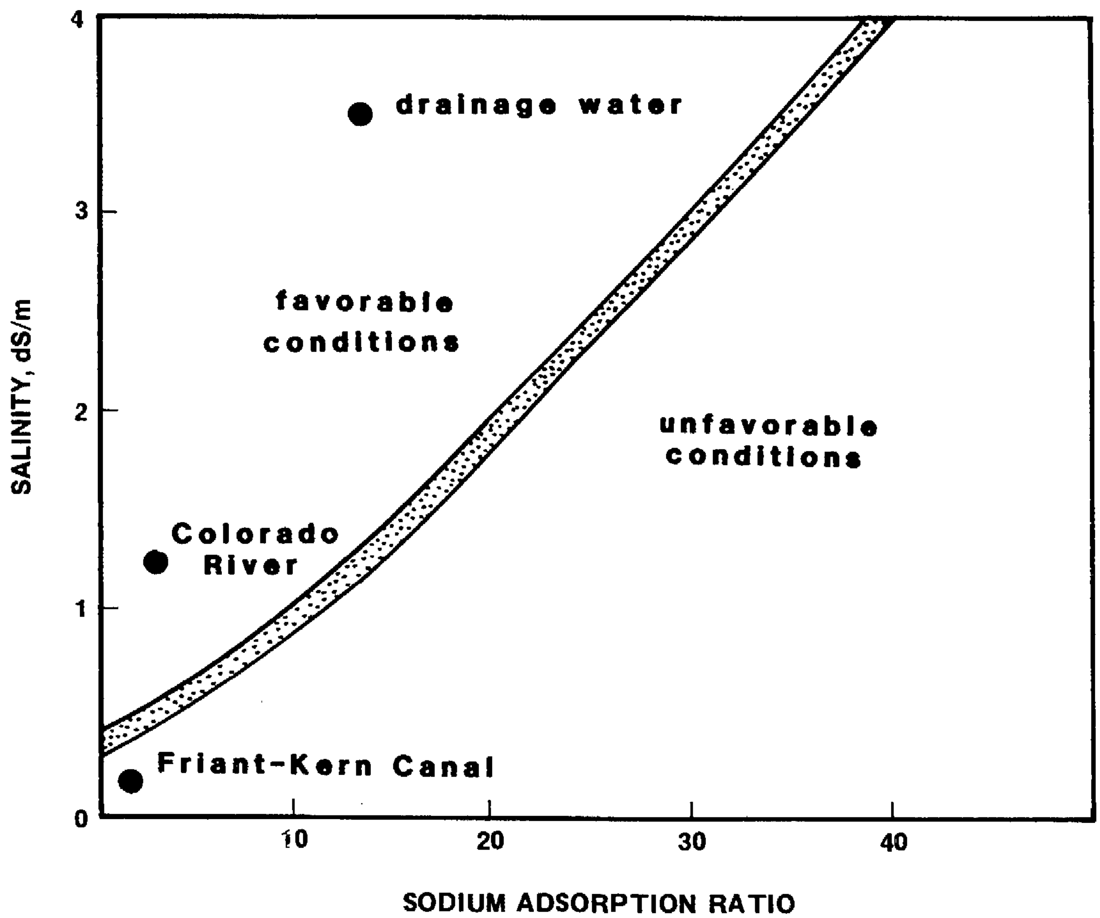

Figure 7-5. Salinity and sodium absorption ratio boundary that divides combinations of both measures into two categories; those which promote good permeability and those which do not. The graph can be used for both irrigation water and soil saturation extract compositions.

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

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

SUMMARY

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

* Verify that soil permeability and drainage are adequate.

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

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

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

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

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

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CHAPTER 8

IRRIGATION SYSTEM DESIGN

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INTRODUCTION

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

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

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

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

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

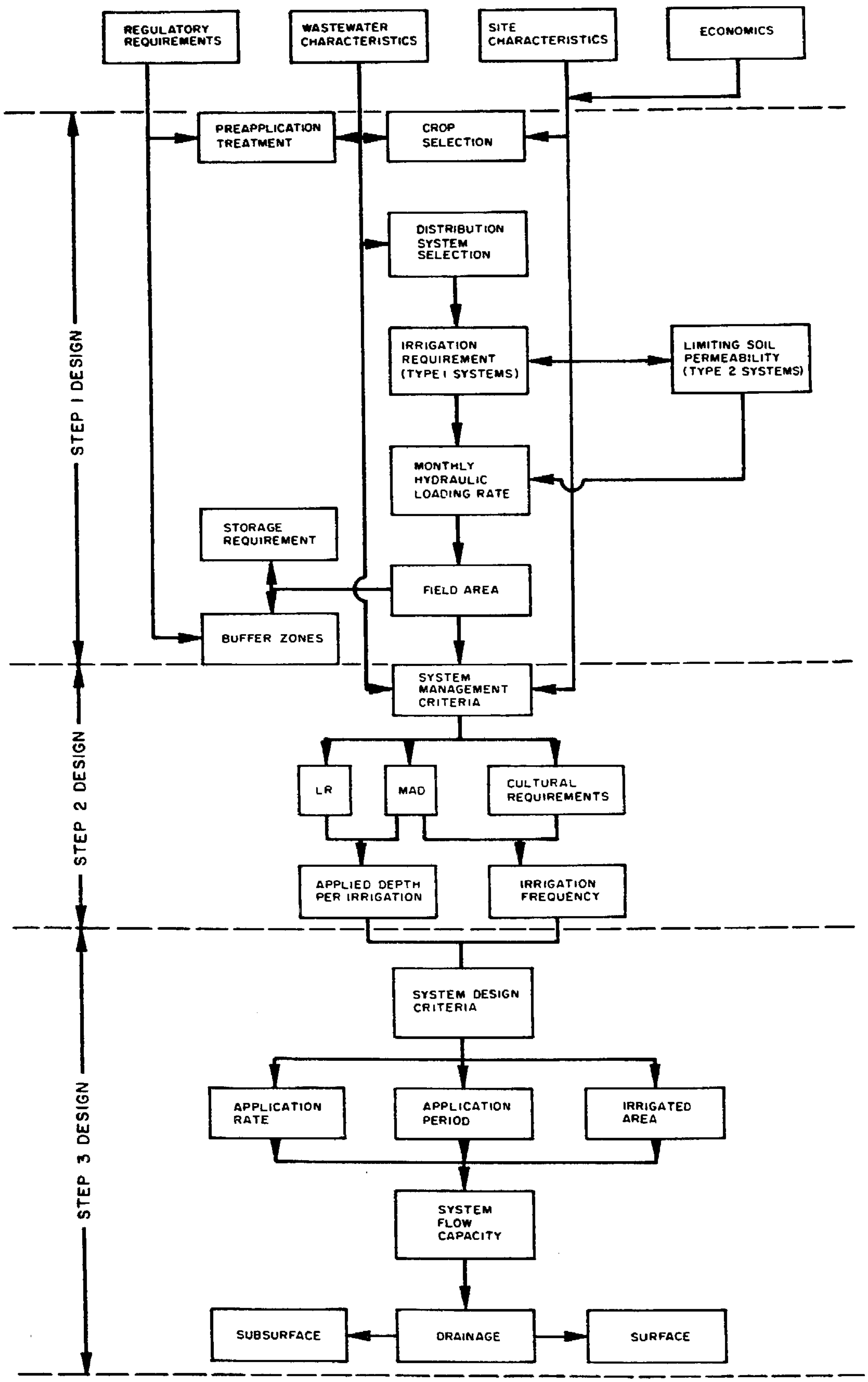

Figure 8-1. Irrigation system design procedure.

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

STEP 1 DESIGN--LAND AREA AND STORAGE REQUIREMENTS

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

Type 1 Systems

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

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

Crop Selection

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

Distribution System Selection

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

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

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

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

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

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

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

Net Irrigation-Water Requirement

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

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

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

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

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

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

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

where

R = net irrigation-water requirement, inch

ET = crop evapotranspiration, inch

P = precipitation, inch

LR = leaching requirement, %

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

Total Irrigation-Water Requirement

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

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

where D = total irrigation-water requirement, inch

R = net irrigation-water requirement

E_u = unit application efficiency for distribution systems, %

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

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

Hydraulic Loading Rate

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

Nitrogen Loading Limits

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

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

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

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

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

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

b. LR = 10%.

c. E_u = 80%.

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

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

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

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

b. LR = 0%.

c. E_u = 80%.

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

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

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

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

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

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

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

2. Compare the value of $L_{w(n)}$ with the annual sum of $L_{w(1)}$ calculated previously (see Tables 8-3 and 8-4). If $L_{w(n)}$ is equal to or greater than annual $L_{w(1)}$, use annual $L_{w(1)}$ for design. If $L_{w(n)}$ is less than annual $L_{w(1)}$, the designer has three options available to increase $L_{w(n)}$ sufficiently to meet the gross irrigation-water requirements or $L_{w(1)}$:
   a. Reduce the concentration of applied nitrogen (C_n) through preapplication treatment (see Chapter 2).
   b. Select a different crop with a higher nitrogen uptake (U) or use a double crop combination for annual crops.
   c. Demonstrate through use of models that sufficient mixing and dilution will occur with the existing groundwater to permit higher values of percolate nitrogen (C_p) to be used in Equation 8-3.

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

Example 8-1. Nitrogen loading limits.

<u>Conditions</u>

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

Example 8-1 (Continued).

5. Denitrification loss fraction (f) = 0.20

Calculations

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

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

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

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

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

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

$L_{w(1)}$ = 43.4

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

Field Area Requirements

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

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

where A_w = field area, acre

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

MG = million gallons

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

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

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

Type 2 Systems

For Type 2 systems, the design steps are:

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

Crop Selection

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

Distribution System Selection

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

Allowable Percolation Rate

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

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

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

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

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

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

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

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

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

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

Maximum Allowable Hydraulic Loading Rate

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

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

where L_w = wastewater hydraulic loading rate, inch/month

$ET - P$ = net evapotranspiration, inch/month

W_p = allowable percolation rate, inch/month

The steps in the procedure are:

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

Nitrogen Loading Limits

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

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

Field Area Requirements

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

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

Other Land Area Requirements

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

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

Storage Requirements

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

Estimation of Storage Volume Requirements

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

c. Rounding error. Assume zero.

d. Maximum storage month.

Final Design Storage Volume Calculations

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

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

Calculations

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

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

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

For the example, assume d_s = 12 ft

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

$$= 18 \text{ acres}$$

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

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

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

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

For the example, assume seepage = 0.

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

Example 8-2 (Continued).

3. Tabulate the volume of wastewater available each month (Q_m) accounting for any expected monthly flow variations (see column 3).

4. Calculate an adjusted field area to account for annual net gain/loss in storage volume:

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

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

a. Maximum design storage volume.

Example 8-2 (Continued).

$$A_w' = \frac{\Sigma Q_m + \Sigma \Delta V_s}{(L_w)\ (\frac{1}{12})}$$

where A_w' = adjusted field area, acre

$\Sigma \Delta V_s$ = annual net storage gain/loss, acre ft

ΣQ_m = annual available wastewater, acre ft

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

For the example:

$$A_w = \frac{1,116.9 - 37.3}{(99)\ (\frac{1}{12})}$$

$= 131$ acres

Note: The final design calculation reduced the field area from 135 acres to 131 acres.

5. Calculate the adjusted monthly volume of applied wastewater using the design monthly hydraulic loading rate and adjusted field area:

$$V_w = (L_w)(A_w')/12 \text{ inches/ft}$$

where V_w = monthly volume of applied wastewater, acre ft

L_w = design monthly hydraulic loading rate, inch

A_w' = adjusted field area, acre

Results are tabulated in column 4 of Table 8-7.

6. Calculate the net change in storage each month by subtracting the monthly applied wastewater (V_w) from the sum of available wastewater (Q_m) and net storage gain/loss (ΔV_s) in the same month. Results are tabulated in Column 5 of Table 8-7.

7. Calculate the cumulative storage volume at the end of each month by adding the change in storage during one month to the accumulated total from the previous month. The computation should begin with the cumulative storage equal to zero at the beginning of the largest storage period. The maximum monthly cumulative volume is the storage volume requirement used for design. Results are tabulated in Column 6 of Table 8-7.

Design storage volume = 243.4 acre ft

Off-line Storage

In some cases, it may be allowable to irrigate with primary effluent, but primary effluent requires additional treatment prior to storage (see Chapter 2). By arranging the piping so that storage can be bypassed, it is possible to irrigate directly with primary effluent. This arrangement is termed off-line storage and is shown schematically in Figure 8-2.

STEP 2 DESIGN--IRRIGATION REQUIREMENTS AND SCHEDULING

The irrigation system design parameters common to all distribution systems to be determined during Step 2 design are:

1. Depth of water applied per irrigation
2. Irrigation frequency

A Step 2 design example is presented at the end of this section for Type 1 and Type 2 systems.

Depth of Water Applied per Irrigation

The depth of water applied during an irrigation event is the total irrigation requirement per irrigation. Determination of this design parameter requires knowledge of two factors: (1) the available water capacity (AWC) of the soil in the root zone of the plant and (2) the management-allowed deficit of water in the root zone before irrigation.

The water available for plant use is defined as the difference in soil water content at "field capacity" and the "wilting point." The moisture remaining in the soil at 15 bars tension is referred to as the wilting point moisture.

The AWC varies primarily as a function of soil texture. The normal ranges of AWC for California soils of different textures are reported in Table 8-8. Actual measured values are preferred, but the values in Table 8-8 may be used in the absence of measured values. The total available water (TAW) in the root zone may be computed by multiplying the AWC by the depth of the root zone.

Information on soil texture, depth, and available water capacity (AWC) is available from published soil surveys prepared by the USDA Soil Conservation Service and Cooperative Extension. Reports are available at most city and county libraries or from the local office of the SCS or Cooperative Extension.

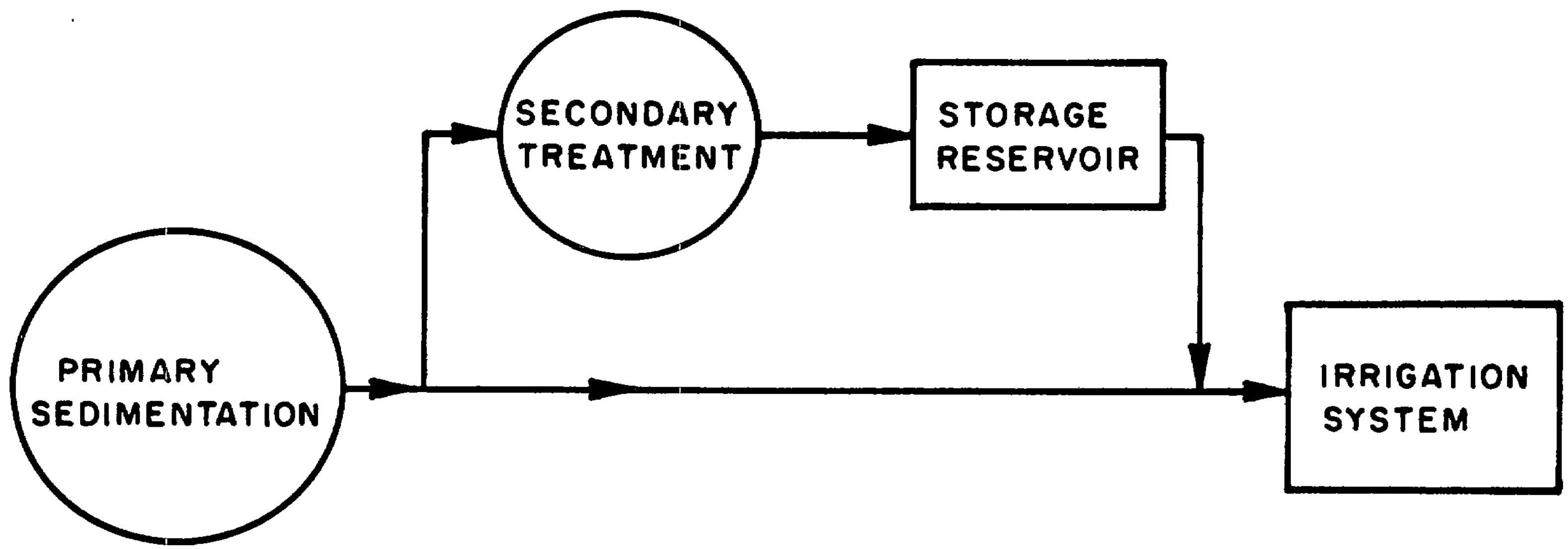

Figure 8-2. Schematic flow diagram for off-line storage.

Table 8-8. Available water capacity for California soils related to texture (inch/ft).

Textural class	Available water capacity
Peat and muck	2.4 - 3.6
Clay > 60%	1.4 - 1.8
Clay < 60%	1.7 - 2.0
Silty clay	1.7 - 2.0
Sandy clay	1.6 - 2.0
Silty clay loam	2.0 - 2.5
Clay loam	2.0 - 2.5
Sandy clay loam	1.7 - 2.2
Silt loam	1.8 - 2.4
Loam	1.7 - 2.2
Very fine sandy loam	1.7 - 2.0
Fine sandy loam	1.6 - 1.8
Sandy loam	1.2 - 1.6
Coarse sandy loam	1.1 - 1.4
Loamy very fine sand	1.1 - 1.3
Loamy fine sand	1.0 - 1.3
Loamy sand	0.7 - 1.0
Loamy coarse sand	0.6 - 0.8
Very fine sand	0.7 - 1.0
Fine sand	0.6 - 1.0
Sand	0.6 - 1.0
Coarse sand	0.4 - 0.8

The percentage or corresponding depth of the total available soil water that is allowed to be used by the plant before an irrigation is scheduled is referred to as the management-allowed deficit (MAD). The MAD is usually the maximum depletion that will not result in reduced crop yield or quality. The usual range of MAD is from 30% to 50% of the available water from the root zone of the crop. For annual crops, the MAD varies by stage of growth and is reduced during critical stages of plant growth. Cooperative Extension advisers should be consulted for recommended values of MAD for specific crops.

Irrigation systems are normally designed to "refill" the soil water "reservoir" when the amount of water extracted from the "reservoir" equals the MAD. This net moisture to be replaced by irrigation may be calculated using the following equation:

$$D_{(net)} = TAW \times \left(\frac{MAD}{100}\right) \qquad [8\text{-}7]$$

where $D_{(net)}$ = net depth of water to be replaced by irrigation, inch

TAW = total available water in the plant root zone, inch

MAD = management allowed deficit, %

To determine the depth of water to be applied during an irrigation for Type 1 systems, the factors leaching requirement (LR) and unit application efficiency (E_u) must be considered. These factors are discussed in Step 1 design. The total depth of application may be computed using the following equation:

$$D = \frac{D_{(net)} + \left(D_{net} \times \frac{LR}{100}\right)}{\left(\frac{E_u}{100}\right)} \qquad [8\text{-}8]$$

where D = depth of water applied during the irrigation, inch

$D_{(net)}$ = net depth of water to be replaced by the irrigation, inch

LR = leaching requirement, %

E_u = unit application efficiency, %

For Type 2 systems, the total depth of water applied per irrigation depends on the monthly hydraulic loading rate determined in Step 1 design and the irrigation frequency for the month according to the following equation:

$$D = L_{w(m)} \times \frac{t_m}{30} \qquad [8\text{-}9]$$

where D = total depth of water applied per irrigation, inch

$L_{w(m)}$ = monthly hydraulic loading rate for month (m)

t_m = maximum time between irrigations for month (m), day

Irrigation Frequency

Irrigation frequency refers to the number of days between irrigations. In practice, growers schedule irrigations or determine irrigation frequency by one of three techniques:

1. Fixed calender schedules developed by growers based on experience.
2. Field monitoring of the soil moisture content using instruments (tensiometers, resistance blocks, neutron probe) or soil sampling.
3. Water balance calculations using soil available water capacity and evapotranspiration data.

For purposes of design, the third method, water balance calculations, is used to determine irrigation frequency. The design of the irrigation system is based on the minimum irrigation frequency during the period of peak evapotranspiration demand. The irrigation frequency at peak ET can be calculated from the $D_{(net)}$ and the peak ET rate using the following equation:

$$t_p = \frac{D_{(net)}}{ET_{(peak)}} \qquad [8\text{-}10]$$

where t_p = maximum time between irrigations at peak ET, day

$D_{(net)}$ = net depth of water to be replaced by irrigation, inch

$ET_{(peak)}$ = peak daily ET rate of the crop, inch/day

Procedures for estimating the peak daily ET rate of the crop during any month are described in detail in Chapter 5. The value of $D_{(net)}$ must be known to use the procedure in Chapter 5 for estimating $ET_{(peak)}$.

In general, irrigation systems should be designed so that the irrigation cycle can be completed in less time than t_p to allow a safety factor for system down time and for cultural operations that must be performed. If the system must run continuously in order to meet the crop needs, down time may result in crop damage and reduced yields. A 25% design safety factor is usually considered adequate, although some cultural practices, such as haying, may require as much as 50% reduction in time allowed between irrigations. Thus, the design irrigation frequency may be calculated as follows:

$$t_d = 0.75\ t_p \qquad [8\text{-}11]$$

where t_d = design time to complete irrigation at peak ET, day

t_p = maximum time between irrigations at peak ET, day

The time between irrigations for any month can be calculated using the following equation:

$$t_m = \frac{D_{(net)}}{ET_{(pm)}} \qquad [8\text{-}12]$$

where t_m = maximum time between irrigations during month (m), day

$D_{(net)}$ = net depth of water to be replaced by irrigation, inch

$ET_{(pm)}$ = peak daily ET rate during month (m), inch/day

For Type 2 systems, equation 8-12 can be used to determine monthly values of t_m to be used in equation 8-9 when calculating (D), total depth of water applied per irrigation.

Example calculations of irrigation requirement and frequency are given in Examples 8-3 and 8-4, respectively.

Example 8-3. Calculation of irrigation requirement and frequency for Type 1 system with a corn crop.

Conditions

1. Effective rooting depth of corn = 4 ft
2. AWC of loam soil = 2 inches/ft
3. MAD at peak ET = 50%
4. Leaching requirement (LR) = 10%
5. Application efficiency (E_a) = 80%

Calculations

1. Determine total available water in root zone

   TAW = (AWC) (depth of root zone)
   = (2 inches/ft) (4 ft)
   = 8 inches

2. Calculate the net depth of applied water

$$D_{(net)} = (TAW)\left(\frac{MAD}{100}\right)$$

$$= (8 \text{ inches})\left(\frac{50}{100}\right)$$

$$= 4 \text{ inches}$$

3. Determine depth of water applied during one irrigation:

$$D = \frac{D_{(net)} + (D_{net} \times \frac{LR}{100})}{\frac{Ea}{100}}$$

$$D = \frac{4 + (4 \times \frac{10}{100})}{\frac{80}{100}}$$

$$D = 5.5 \text{ inches}$$

4. Determine the 10-year frequency peak daily ET for peak month (July) using Figure 5-8 and the value of $D_{(net)}$ (see Chapter 5).

Example 8-3 (Continued).

5. Determine the maximum time between irrigations at peak ET

$$t_p = \frac{D_{net}}{ET_{peak}}$$

$$t_p = \frac{4.0}{0.383}$$

$t_p = 10.4$ days <u>Use 10 days</u>

6. Determine the design time to complete irrigation of the total field area:

$t_d = 0.75\ t_p$

$t_d = 7.5$ days <u>Use 7 days</u>

Example 8-4. Calculation of irrigation requirement and frequency for Type 2 system with a pine tree crop.

<u>Conditions</u>

1. Effective rooting depth = 5 ft
2. AWC of clay loam soil = 2 inches/ft
3. MAD at peak ET = 50%

<u>Calculations</u>

1. Determine total available water in root zone:

   TAW = (AWC) (depth of root zone)

   = (2 inches/ft) (5)

   = 10 inches

2. Calculate the net depth of water applied per irrigation:

$$D_{(net)} = (TAW)\left(\frac{MAD}{100}\right)$$

$$= (10\text{ inches})\left(\frac{50}{100}\right)$$

$$= 5\text{ inches}$$

3. Determine the 10-year frequency peak daily ET for the month (July) using Figure 5-8 and the value for $D_{(net)}$. Values for each month are calculated in the same manner.

   $ET_{pm} = 0.39$ inches/day

Example 8-4 (Continued).

4. Determine the maximum time between irrigations for the month (July).

$$t_m = \frac{D_{(net)}}{ET_{pm}}$$

$$tm = \frac{5 \text{ inch}}{0.39}$$

$t_m = 12.94$ <u>Use 13 days</u>

5. Determine depth of applied water per irrigation for the month (July). Values for other months are calculated in the same manner (see Table 8-5).

$$D = (L_w)\left(\frac{t_m}{30}\right)$$

$$= (14.7 \text{ inches})\left(\frac{13}{30}\right)$$

$$= 6.4 \text{ inches}$$

6. Determine the design time to complete irrigation of the total field area:

$t_d = 0.75\ t_m$

$t_d = 0.75\ (13)$

$t_d = 9.7$ days <u>Use 10 days</u>

STEP 3 DESIGN--DETAILED SYSTEM DESIGN

A summary of references for design of various system components is given in Table 8-9. Design procedures are described in this section in sufficient detail so that system flow capacity can be estimated. Also, the USDA Soil Conservation Service has prepared practice standards covering several aspects of design.

Stationary Sprinkler Systems

Stationary sprinkler systems include solid set systems and periodical lateral move systems (wheel move, hand move laterals). Design parameters for stationary sprinkler systems include the following:

Table 8-9. Summary of references on detailed design of irrigation systems.

Irrigation system component	Reference numbers
General	[2] [6] [10]
Stationary sprinklers	[4] [11] [12]
Moving sprinklers	[5] [11] [12]
Furrow irrigation	[8] [13]
Graded border irrigation	[8] [14]
Drip irrigation	[15]
Tailwater return	[16]
Drainage system	[17] [18] [19]
Storage reservoirs	[20]

1. Application rate
2. Application period
3. Irrigated area
4. System flow capacity
5. Sprinkler selection and spacing
6. Lateral sizing and layout

Application Rate

Application rate of a sprinkler system is the rate at which water is applied expressed in units of inch/hour. Stationary sprinkler systems are designed so that the average application rate over the irrigated area is less than the basic intake rate of the surface soil to prevent runoff. Application rates can be increased when a full crop cover is present. The increase should not exceed 100% of the bare soil application rate [1]. Recommended reductions in application rate for sloping terrain are given in Table 8-10. A practical minimum design application rate is 0.2 inch/hour (0.5 cm/hour).

Table 8-10. Recommended reductions in application rates due to grade [4].

Grade	Application rate reduction,%[a]
0-5	0
6-8	20
9-12	40
13-20	60
over 20	75

a. Percent of level ground application rate.

Application Period

The period of time over which (D) is applied is the application period, and it is a function of (D) and the average rate of application and may be calculated using the following equation:

$$T_a = \frac{D}{I} \qquad [8\text{-}13]$$

where T_a = application period, hour
D = total depth of water applied, inch
I = average application rate, inch/hour

The application rate may be adjusted to yield an application period that is convenient to the operator and compatible with working hours.

Irrigated Area

For stationary systems, water is not normally applied to the entire field area in a single irrigation. Rather, the field area is divided into application plots or zones and water is applied to one zone at a time. Application is rotated among the zones so that the entire field area receives one irrigation within the time period (t_d). The minimum size of the irrigated area may be calculated using the following equation:

$$A_{i(m)} = \frac{(A_w)(T_a)}{(t_d)(24)} \qquad [8\text{-}14]$$

where $A_{i(m)}$ = minimum irrigated area, acre
A_w = total field area, acre
T_a = application period, hour
t_d = design time to complete irrigation, day

Larger irrigated areas can be used, which will result in lower labor requirements but a larger system flow capacity, as described in the next section.

System Flow Capacity

The maximum flow capacity of the system must be determined so that components, such as pipelines and pumping stations, can be sized properly. For stationary sprinkler systems with a constant application rate, the flow capacity of the system can be computed using the following formula:

$$Q = (A_i)(I)(453) \qquad [8\text{-}15]$$

where Q = system flow capacity, gal/min

A_i = irrigated area, acre

I = application rate, inch/hour

Sprinkler Selection and Spacing

For stationary sprinkler systems, the application rate can be expressed as a function of the sprinkler discharge capacity, the spacing of the sprinklers along the lateral, and the spacing of the laterals along the main according to the following equation:

$$I = \frac{(q_s)(96.3)}{(S_s)(S_L)} \qquad [8\text{-}16]$$

where I = application rate, inch/hour

q_s = sprinkler discharge rate, gal/min

S_s = sprinkler spacing along lateral, ft

S_L = lateral spacing along main, ft

Sprinkler selection and spacing determination involves an iterative process. The usual procedure is to select a sprinkler and lateral spacing, then determine the sprinkler discharge capacity required to provide the design application rate at the selected spacing. The required sprinkler discharge capacity may be calculated using Equation 8-13. Manufacturers' sprinkler performance data are then reviewed to determine the nozzle sizes, operating pressures, and wetted diameters of sprinklers operating at the desired discharge rate. The wetted diameters are then checked with the assumed spacings for conformance with spacing criteria. Recommended spacings are based on a percentage of the wetted diameter and vary with the wind conditions. Recommended spacing criteria are given in Table 8-11. References in Table 8-9 should be consulted for details.

Table 8-11. Recommended spacing of sprinklers [4].

Average wind speed	Spacing[a]
mile/hour	% of wetted diameter
0-7	40 (between sprinklers)
7-10	65 (between laterals)
>10	30 (between sprinklers) 50 (between laterals)

a. These values are for high pressure sprinklers. Newer low pressure sprinklers (30 to 40 psi) normally have 10-ft less throw, and an adjustment in lateral spacing is required.

Lateral Sizing and Layout

The size of mainlines and sprinkler lateral pipes must be selected such that the friction loss at the design flow is limited to a predetermined amount. A general practice is to limit all hydraulic losses (static and dynamic) in the main plus lateral to 15% of the operating pressure of the sprinklers. This will result in sprinkler discharge variations of about 10% along any lateral.

When determining the position or layout of the laterals in the field, the topography and the wind direction must be considered. The references in Table 8-9 should be consulted for details.

Traveling Gun Sprinklers

Design parameters for traveling gun sprinklers include:

1. Application rate
2. Irrigation area/unit
3. Unit sprinkler discharge capacity
4. Travel lane spacing
5. Travel speed
6. Number of units
7. System flow capacity

8. Pipe and hose size
9. System layout

Application Rate

Application rates for moving sprinkler systems, such as center-pivot and traveling gun sprinklers, vary with time and space and are necessarily higher than rates for stationary systems, because water is applied at any one point for only a fraction of the total time of irrigation. For traveling guns, the application rate is a function of the sprinkler nozzle characteristics and may be determined from manufacturer performance tables. The minimum design application rate for the smaller sprinkler guns is in the range of 0.25 to 0.30 inch/hour. The largest units have application rates approaching 0.5 inch/hour. It should be noted that part-circle sprinklers are often used to avoid wetting the travel lane ahead of the traveling unit, but the application rate increases in proportion to the reduction in the extent of revolution. Application rates in excess of the basic intake rate of the soil or vegetated surface can be used if allowances are made for (1) higher intake rates at the beginning of application and (2) temporary storage of water on the soil surface. Recommended allowances for surface storage for different slopes are presented in Table 8-12. When surface storage capacity is exceeded, runoff will occur.

Table 8-12. Allowable surface storage values for various slopes [5].

Slope (%)	Allowable surface storage (inch)
1-3	0.3
3-5	0.1

Other Design Parameters

The steps involved in determining the remaining design parameters are outlined as follows:

1. Estimate the area to be irrigated by a single unit. The practical maximum design value is about 80 acres.
2. Estimate the number of hours per day that a unit will be in operation, allowing time (1 hour minimum) to move the unit at the end of each travel lane. This value will depend on individual requirements, but maximum values should not exceed 20 to 22 hours/day.
3. Estimate the sprinkler discharge capacity using the following formula:

$$q_s = \frac{(435)(D_{(total)})(A_i)}{(t_p)\,(T_a)} \qquad [8\text{-}17]$$

where q_s = sprinkler discharge capacity, gal/min
$D_{(total)}$ = depth of water applied per irrigation, inch
A_i = area irrigated per unit
t_p = time between irrigations at peak ET, day
T_a = length of operating time per day, hour

4. Select from manufacturer performance tables a sprinkler size and operating pressure that will provide the estimated discharge capacity. Operating pressures should be greater than 80 lbs/inch^2.
5. Check application rate of selected sprinkler against the basic intake rate of the soil or vegetated surface. Reduce the selected sprinkler discharge capacity as necessary so that the application rate will be compatible with the soil intake rate and surface storage capacity and so that runoff will not occur.
6. Determine the design lane spacing based on the wetted diameter of the selected sprinkler using the spacing criteria given in Table 8-13.

Table 8-13. Recommended maximum lane spacing for traveling gun sprinklers.

Wind Speed (mile/hour)	Lane spacing (% of wetted diameter)
0	80
1-5	70-75
6-10	60-65
>10	50-55

7. Calculate the travel speed of the unit using the following formula:

$$S_p = \frac{(q_s)(1.6)}{(S_t)(D)} \qquad [8\text{-}18]$$

where S_p = travel speed, ft/min
q_s = sprinkler capacity, gal/min
S_t = space between travel lanes, ft
D = depth of water applied per irrigation, inch

8. Calculate the actual area irrigated per unit using the following equation:

$$A_i = \frac{(S_t)(L_t)(t_d)}{43{,}560} \qquad [8\text{-}19]$$

where A_i = area irrigated per unit, acre
S_t = lane spacing, ft
L_t = average travel distance per day, ft
t_d = design time to complete irrigation, day (see equation 8-11)

9. Calculate the total number of units required for the complete system using the following equation:

$$N_u = \frac{A_w}{A_i} \qquad [8\text{-}20]$$

where N_u = total no. of units required

A_w = field area, acre

A_i = area irrigated per unit

10. Determine the flow capacity for the total system as follows:

$$Q = (q_s)(N_u) \qquad [8\text{-}21]$$

where Q = system flow capacity, gal/min

11. Select sizes for supply pipe and flexible hose to minimize total capital and operating costs.
12. Layout mainlines to minimize length and layout travel lanes perpendicular to the prevailing wind.

Center-Pivot Sprinklers

Design parameters for center-pivot systems include:

1. Application rate
2. Irrigated area per unit
3. Water flow per unit
4. Rotational speed of the lateral
5. Sprinkler sizing and spacing

Center-pivot systems are not widely used in California and therefore are not discussed here. System design has been discussed by Dillon et al. [5].

Surface Systems

Furrow Distribution

The design procedure for furrow systems is empirical and is based on past experience with good irrigation systems and field evaluation of operating systems. For more detailed design procedures, the designer is referred to references in Table 8-9.

The design variables for furrow systems include:

1. Furrow grade
2. Furrow spacing

3. Furrow length
4. Furrow stream size
5. Application period
6. Irrigated area
7. System flow capacity

The furrow grade will depend on the site topography. A grade of 2% is the recommended maximum for straight furrows. Furrows can be oriented diagonally across fields to reduce grades. Contour furrows or corrugations can be used with grades in the range of 2% to 10%.

The furrow spacing depends on the water intake characteristics of the soil. The principal objective in selecting furrow spacing is to make sure that the lateral movement of the water between adjacent furrows will wet the entire root zone before it percolates beyond the root zone. Suggested furrow spacings based on different soil and subsoil conditions are given in Table 8-14.

The length of the furrow should be as long as needed to permit reasonable uniformity of application, because labor requirements and capital costs increase as furrows become shorter. Suggested maximum furrow lengths for different grades, soils, and depths of water applied are given in Table 8-15.

The furrow stream size or application rate is expressed as flow rate per furrow. The optimum stream size is usually determined by trial and adjustment in the field after the system has been installed [6]. Highest application efficiency generally can be achieved by starting the application with the largest stream size that can be safely carried in the furrow. Once the stream has reached the end of the furrow, the application rate can be reduced or cut back to reduce the quantity of runoff that must be handled. As a general rule, it is desirable to have the stream size large enough to reach the end of the furrow within one-fourth of the time required for infiltration, which is equivalent to one-fifth of the total application period.

Supply pumps and transmission systems should be designed to provide the maximum allowable stream size, which is generally limited by erosion considerations when grades are greater than 0.3%. The maximum nonerosive stream size can be estimated from the equation:

Table 8-14. Optimum furrow spacing [7].

Soil condition	Optimum spacing (inches)
Coarse sands--uniform profile	12
Coarse sands--over compact subsoils	18
Fine sands to sandy loams--uniform	24
Fine sands to sandy loams--over more compact subsoils	30
Medium sandy-silt loam--uniform	36
Medium sandy-silt loam--over more compact subsoils	40
Silty clay loam--uniform	48
Very heavy clay soils--uniform	36

Table 8-15. Suggested maximum lengths (in feet) of cultivated furrows for different soils, and depths of water to be applied [8].

Furrow grade (%)	Average depth of water applied (inches)											
	Clays				Loams				Sands			
	3	6	9	12	2	4	6	8	2	3	4	5
0.05	3,000	1,300	1,300	1,300	400	900	1,300	1,300	200	300	500	600
0.1	1,100	1,400	1,500	1,600	600	1,100	1,400	1,500	300	400	600	700
0.2	1,200	1,500	1,700	2,000	700	1,200	1,500	1,700	400	600	800	1,000
0.3	1,300	1,600	2,000	2,600	900	1,300	1,600	1,900	500	700	900	1,300
0.5	1,300	1,600	1,800	2,400	900	1,200	1,500	1,700	400	600	800	1,000
1.0	900	1,300	1,600	1,900	800	1,000	1,200	1,500	300	500	700	800
1.5	800	1,100	1,400	1,600	700	900	1,100	1,300	250	400	600	700
2.0	700	900	1,100	1,300	600	800	1,000	1,100	200	300	500	600

$$q_e = 10/G \quad [8\text{-}22]$$

where q_e = maximum unit stream size, gal/min
G = grade, %

For grades less than 0.3%, the maximum allowable stream size is governed by the flow capacity of the furrow, estimated as follows:

$$q_c = (74)(F_a) \quad [8\text{-}23]$$

where q_c = furrow flow capacity, gal/min
F_a = cross-sectional area of furrow, ft²

The application period is the time needed for water to infiltrate to the desired depth plus the time required for the stream to advance to the end of the furrow. The time required for infiltration depends on the water intake characteristics of the furrow. There is no standard method for estimating the furrow intake rate. The recommended approach is to determine furrow intake rates and infiltration times by field trials as described elsewhere [6].

The irrigated area per irrigation depends on the number of applications that can be made per day, which in turn depends on available labor and the application period. The irrigated area may be calculated as follows:

$$A_i = \frac{A_w}{(N_a)(t_d)} \quad [8\text{-}24]$$

where A_i = irrigated area per irrigation, acre
A_w = field area, acre
N_a = no. of applications per day
t_d = design time between irrigations, day

System flow capacity is a function of the number of furrows in the irrigated area and the furrow stream size. The number of furrows used may be calculated as follows:

$$N_f = \frac{(A_i)(43{,}560)}{(L_f)(S_f)} \quad [8\text{-}25]$$

where N_f = no. of furrows per irrigated acres

A_i = irrigated area, acre

L_f = furrow length, ft

S_f = furrow spacing, ft

System flow capacity may then be computed as follows:

$$Q = (N_f)(q_e \text{ or } q_c) \qquad [8\text{-}26]$$

where Q = system capacity, gal/min

N_f = no. of furrows per irrigation

q_e, q_c = design maximum furrow stream size, gal/min

Graded Border Distribution

Quasi-rational design procedures have been developed by the SCS for all variations of border distribution systems and are given in the references in Table 8-9.

The design variables for graded border distribution are:

1. Grade of the border strip
2. Width of the border strip
3. Length of the border strip
4. Unit stream size
5. Application period
6. Irrigated area
7. System flow capacity

Graded border distribution can be used on grades up to about 7%, but grades of 2% or less are most common. Terracing of graded borders can be used for grades up to 20%.

The widths of border strips are often selected for compatibility with farm implements, but they also depend to a certain extent upon grade and soil type, which affect the uniformity of distribution across the strip. Guidelines for estimating strip widths are presented in Tables 8-16 and 8-17.

The appropriate length of a border strip depends on the grade, allowable stream size, the depth of water applied, the intake characteristics of the soil, and the configuration of the field. The guidelines presented in Tables 8-16 and 8-17 may be used to make initial estimates of border length.

Table 8-16. Design guidelines for graded border distribution, deep-rooted crops [8].

Soil type and infiltration rate	Grade (%)	Unit flow per 1 ft of strip width (ft^3/sec)	Avg depth of water applied	Border strip width (ft)	Border strip length (ft)
SANDY Infiltration rate of 1+ inch/hour	0.4-0.6 0.4-0.6 0.6-1.0	0.09-0.11 0.09-0.11 0.06-0.09	4 4 4	30-40 30-40 20-30	200-300 200-300 250
LOAMY SAND Infiltration rate of 0.75 to 1 inch/hour	0.2-0.4 0.4-0.6 0.6-1.0	0.07-0.11 0.06-0.09 0.03-0.06	5 5 5	40-100 25-40 25	250-500 250-500 250
SANDY LOAM Infiltration rate of 0.5 to 0.65 inch/hour	0.2-0.4 0.4-0.6 0.6-1.0	0.06-0.08 0.04-0.07 0.02-0.04	6 6 6	40-100 20-40 20	300-800 300-600 300
CLAY LOAM Infiltration rate of 0.25 to 0.5 inch/hour	0.2-0.4 0.4-0.6 0.6-1.0	0.03-0.04 0.02-0.03 0.01-0.02	7 7 7	40-100 20-40 20	600-1,000 300-600 300
CLAY Infiltration rate of 0.10 to 0.25 inch/hour	0.2-0.3	0.02-0.04	8	40-100	1,200+

Table 8-17. Design guidelines for graded border distribution, shallow-rooted crops [8].

Soil profile	Grade (%)	Unit Flow per 1 acre of strip width (ft^3/sec)	Avg depth of water applied (inches)	Border strip Width (ft)	Border strip Length (ft)
CLAY LOAM 24 inches deep over permeable subsoil	0.15-0.6 0.6 -1.5 1.5 -4.0	0.06-0.08 0.04-0.07 0.02-0.04	2-4 2-4 2-4	15-60 15-20 15-20	30-600 300-600 300
CLAY 24 inches deep over permeable subsoil	0.15-0.6 0.6 -1.5 1.5 -4.0	0.03-0.04 0.02-0.03 0.01-0.02	4-6 4-6 4-6	15-60 15-20 15-20	600-1,000 600-1,000 600
LOAM 6 to 18 inches deep over hardpan	1.0 -4.0	0.01-4.0	1-3	15-20	300-1,000

The unit stream size is expressed as a flowrate per unit width of border strip, gal/min·ft or ft³/sec·ft. The optimum stream size is best determined by field trials as described in elsewhere [6]. The range of stream sizes given in Tables 8-16 and 8-17 for various soil and crop conditions may be used for initial design. Procedures given in the references in Table 8-9 may be used to obtain a more accurate estimate of stream size.

The application period necessary to apply the desired depth of water may be determined by using the following equation:

$$t_a = \frac{(L)(D)}{(96.3)(q_u)} \qquad [8\text{-}27]$$

where t_a = application period, hour
L = border strip length, ft
D = depth of applied water, inch
q_u = unit stream size, gal/min·ft

The irrigated area may be determined using Equation 8-24 in the same manner as described for furrow distribution systems.

System flow capacity depends on the number of strips in the irrigated area, the width of the strips, and the unit stream size. The system flow capacity may be calculated as follows:

$$Q = \frac{(A_i)(q_u)(43,560)}{L} \qquad [8\text{-}28]$$

where Q = system flow capacity, gal/min
A_i = irrigated area, acre
L = length of border strip, ft
q_u = unit stream size, gal/min·ft

Materials of Construction

Distribution equipment must be durable and able to function with wastewater that may be high in salinity and suspended solids. Equipment, particularly piping and nozzles, should be corrosion-resistant and free from malfunctions caused by suspended particles and organics in the water supply. Aluminum pipe should be clad inside with a corrosion-resistant lining.

Tailwater Return Systems

Runoff of reclaimed wastewater from the irrigated site is normally prohibited by regulatory agencies. Sprinkler distribution systems should be designed so that runoff of applied water does not occur. Surface systems, however, will almost always produce some runoff or tailwater that must be contained on the site. A typical tailwater return system consists of a sump or reservoir, a pump or pumps, and return pipeline. Guidelines for estimating tailwater volume, the duration of tailwater flow, and suggested maximum design tailwater volume are presented in Table 8-18. Pumps can be any convenient size, but a minimum capacity of 25% of the distribution system flow capacity is recommended [9]. The references in Table 8-9 may be consulted for further details.

Table 8-18. Recommended design factors for tailwater return systems [9].

Class	Rate (inch/hour)	Texture range	Max duration of tailwater flow	Estimated tailwater volume	Suggested max design tailwater volume
			% of application time	% of application volume	% of application volume
Very slow to slow	0.06-0.20	Clay to clay loam	33	15	30
Slow to moderate	0.20-0.60	Clay loam to silt loam	33	25	50
Moderate to moderately rapid	0.60-6.0	Silt loams to sandy loam	75	35	70

Subsurface Drainage Systems

Assessing the need for a subsurface drainage system is discussed, followed by a brief discussion of design considerations.

Need for Subsurface Drainage

Subsurface drainage is necessary to provide a root zone environment conducive to good plant growth. The existence of a high water table (depth to water table less than 10 ft) indicates poor subsurface drainage, so subsurface drains should be installed to drain the soil properly. If no water table or a deep water table exists, then subsurface conditions should be evaluated to determine if drainage problems due to irrigation will occur in the future.

The first thing to consider in this investigation is the soil profile. What is the permeability of the soil down to at least 10 feet? Are there significant differences in permeability due to clay lenses or hard pans? Clay lenses or hard pans can cause a perched water table, which will result in a drainage problem, even though the area-wide depth to the water table is 10 feet or deeper. Changes in soil permeability with depth, such as a light-texture soil overlying a clay soil, can also create drainage problems. If conditions such as described above exist, then drainage problems may also exist and provisions should be made for the installation of a subsurface drainage system.

If an area-wide water table exists, one should evaluate existing flow patterns by installing a network of observation wells and determining the elevation of the water table at each well. This will provide information on the direction of flow, which may in turn help determine the type of drainage system needed. If the data from the observation wells show little change in elevation throughout the area, this may indicate that area-wide subsurface drainage is poor and that the potential exists for drainage problems if the land is irrigated. The flow analysis may also provide data on sources or potential sources of drainage water. If the flow patterns indicate that irrigation of upperlying lands is contributing to the groundwater, a subsurface drainage system may be needed for the lowerlying fields. However, an interceptor drain installed at the upper end of the site in question may be all that is necessary to remove any drainage water.

The location of the site with respect to canals, ditches, rivers, ponds, and other bodies of water should be also considered. Seepage from these bodies of water may contribute substantially to any present or potential drainage problems.

The potential volume of drainage water should also be considered. How much rainfall (and frequency) occurs at the site? What is the leaching fraction needed to control soil salinity?

Drainage System Design Considerations

If the preliminary investigation indicates that drainage problems exist or will occur in the future, then a subsurface drainage system should be installed. However, before any installation, the method of drainage disposal water should be determined. In some areas, deep open-ditch drains are used to convey the drainage water to some disposal point. Water from the subsurface drainage system discharges into these ditches by gravity flow. Where gravity flow is not possible, then a sump is used to collect the drainage water that flows into the sump. A sump pump then discharges the water to the conveyance system.

If no conveyance system designed specifically for subsurface drainage water exists, then a method for disposing of the water must be found. Possible methods include discharging into the irrigation water conveyance system, into streams or channels, recirculating the water back onto the irrigated land, discharging to a marsh, or using evaporation ponds. The limiting factor on discharging drain water into surface water channels (such as rivers, canals, irrigation ditches) is the quality of the drain water. It may be possible to discharge good-quality drain water, provided the necessary discharge permits are obtained. If the drain-water quality is poor and no means exists to discharge the water without adversely affecting quality of water for downstream users, then on-site disposal must be considered. If this is not possible, then sites with better drainage conditions should be considered.

Once it has been determined that subsurface drainage is necessary and that the drainage water can be disposed of properly, the next step is to design a subsurface system that will provide the needed water-table control. This involves selecting the proper depth and spacing of the drains, which in turn will depend on the crop type, soil type, quality of the subsurface water, quality of the irrigation water, and volume of drainage water.

The depth of the water table needed to maintain a good root-zone environment will depend on factors such as crop type, soil type, and quality of subsurface and applied water. Generally, under arid conditions such as the San Joaquin Valley, the water-table depth is controlled to prevent excessive accumulation of salts due to upward flow of saline groundwater into the root zone. The quality of the subsurface water is usually much poorer than that of the applied water. Recommended depths to the water table are listed in Table 8-19. Also, where saline high water tables exist, salt-tolerant crops should be used.

Table 8-19. Recommended depth (in meters) to water table for arid areas [8].

Crop	Fine-textured soil (permeable)	Medium-textured soil	Light-textured soil
Field	0.9	1.2	0.9
Vegetable	0.9	1.1	0.9
Tree	1.4	1.4	1.1

Note: During fallow periods, the water table should be controlled at a depth of 1.4 meters for light- and fine-textured soils and 1.5-1.8 meters for medium-textured soils.

In some areas, however, such as along the central California coast, drainage may be needed only to prevent waterlogging of the soil and to improve trafficability. In other areas, drains are operated only during the winter months when large amounts of rainfall occur. Drainage water in these areas is generally of good quality.

The spacing of the drains required to maintain the desired water table level will depend on the volume of water to be drained, the hydraulic conductivity of the soil, and the elevation difference between the water table at the midpoint between drains and the drain tubing. The hydraulic conductivity is a measure of the ease at which water moves through the soil. Soils such as sand generally have high hydraulic conductivities, while clay soils generally have low conductivities; however, these are not necessarily true for all cases. In any event, it is recommended that measurements of hydraulic conductivity be made at the location in question (see Chapter 4).

The auger-hole test is the most common and easiest method of measuring in-situ hydraulic conductivity. The method consists of augering a hole down to at least the desired depth of the drain (Figure 8-3), allowing the water in the hole to come into equilibrium with the water table and then rapidly emptying the hole. After the hole is emptied, the water level in the hole is measured with time. These data are then plotted as depth to the water in the hole versus time, and the slope of this curve is determined for small times (Figure 8-4). The slope is then used with the following equation:

$$K = -C \times \text{slope of line at small times} \qquad [8\text{-}28]$$

to calculate the hydraulic conductivity. The term C depends on the shape of the auger hole, the depth of the hole below the water table, the depth of water in the hole after the initial emptying, and the location of impermeable or permeable layers with respect to the bottom of the auger hole. Values of C for various conditions are presented in Table 8-20.

An estimate of the volume of water to be drained can be made from an estimate of the volume of deep percolation using the following equation:

$$q = \frac{(P/100)_i}{F} \qquad [8\text{-}29]$$

where q = drainage coefficient (volume of water to be drained in 24 hours)

i = depth volume of applied water

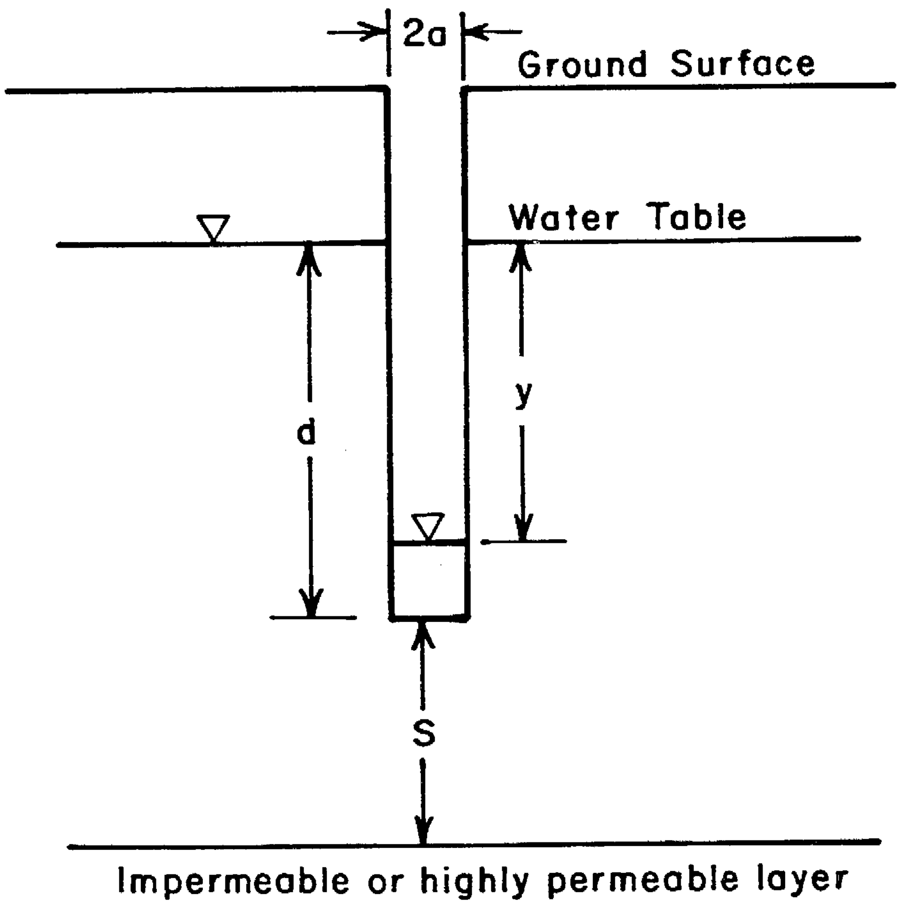

Figure 8-3. Auger-hole test.

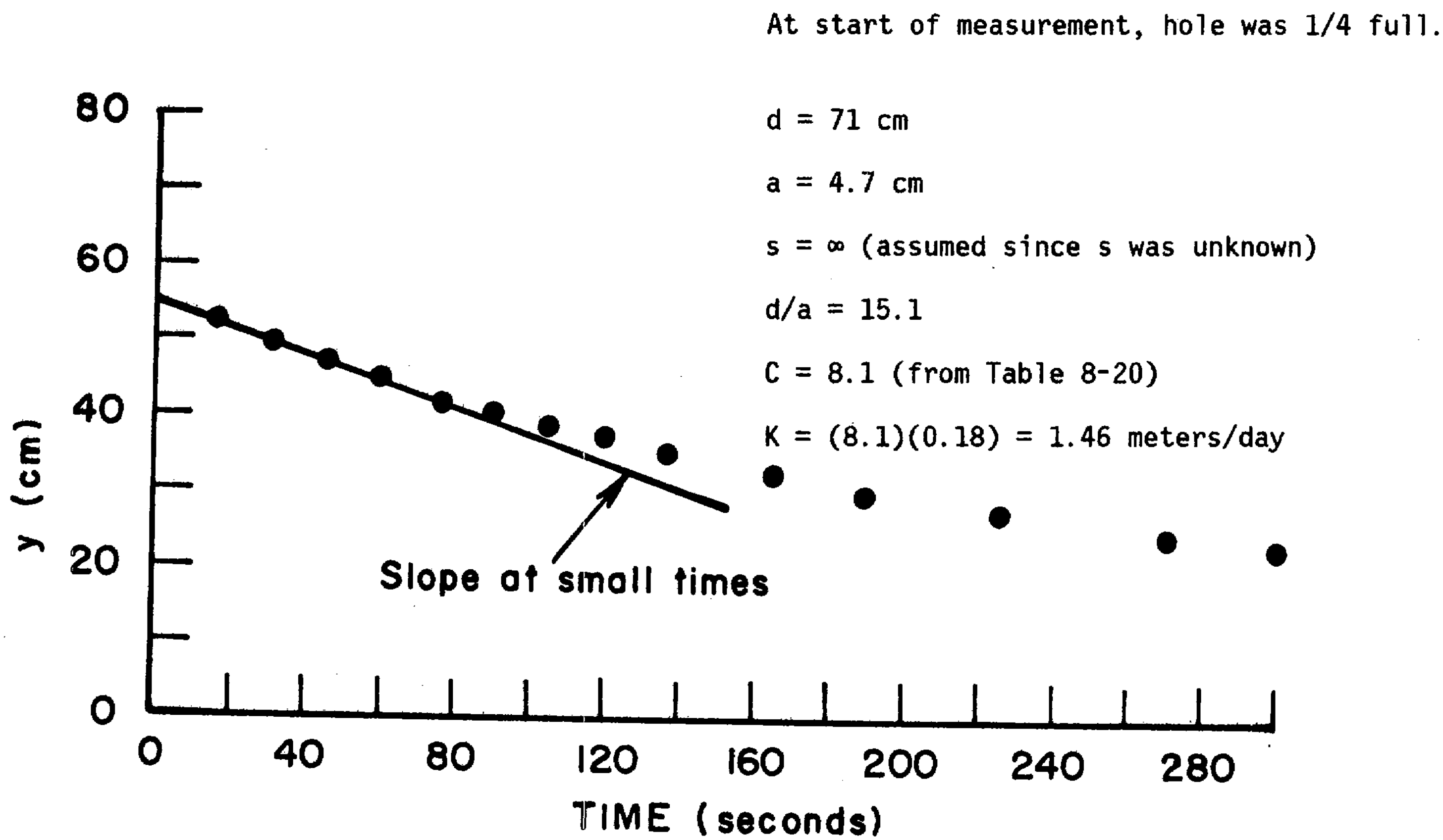

Figure 8-4. Example of auger hole method for measuring hydraulic conductivity.

Table 8-20. Values of C. The rate of rise of water in the auger hole is measured in cm/sec, this value is multiplied by C to find the value k in meters/day of the hydraulic conductivity of the soil surrounding the auger hole [21].

d/a		Impermeable barrier at s/d =								s/d = ∞ (infinite medium)	Gravel at s/d =			
		0.00	0.05	0.10	0.20	0.50	1.00	2.00	5.00		5.00	2.00	1.00	0.50
1.	empty	447.0	423.0	404.0	375.0	323.0	386.0	264.0	255.0	254.0	252.0	241.0	213.0	166.0
	1/4 full	469.0	450.0	434.0	408.0	360.0	324.0	303.0	292.0	291.0	289.0	278.0	248.0	198.0
	1/2 full	555.0	537.0	522.0	497.0	449.0	411.0	386.0	380.0	379.0	377.0	359.0	324.0	264.0
2.	empty	186.0	176.0	167.0	154.0	134.0	123.0	118.0	116.0	115.0	115.0	113.0	106.0	91.0
	1/4 full	196.0	187.0	180.0	168.0	149.0	138.0	133.0	131.0	131.0	130.0	128.0	121.0	106.0
	1/2 full	234.0	225.0	218.0	207.0	188.0	175.0	169.0	167.0	167.0	166.0	164.0	156.0	139.0
5.	empty	51.9	58.6	46.2	52.8	38.7	36.9	36.1		35.8		35.5	34.6	32.4
	1/4 full	54.8	52.0	49.9	46.8	42.8	41.0	40.2		40.0		39.6	38.6	36.3
	1/2 full	66.1	63.4	61.3	58.1	53.9	51.9	51.0		50.7		50.3	49.2	46.6
10.	empty	18.1	16.9	16.1	15.1	14.1	13.6	13.4		13.4		13.3	13.1	12.6
	1/4 full	19.1	18.1	17.4	16.5	15.5	15.0	14.8		14.8		14.7	14.5	14.0
	1/2 full	23.3	22.3	21.5	20.6	19.5	19.0	18.8		18.7		18.6	18.4	17.8
20.	empty	5.91	5.53	5.30	5.06	4.81	4.70	4.66		4.64		4.62	4.58	4.46
	1/4 full	6.27	5.94	5.73	5.50	5.25	5.15	5.10		5.08		5.07	5.02	4.89
	1/2 full	7.76	7.34	7.12	6.88	6.60	6.48	6.43		6.41		6.39	6.34	6.19
50.	empty	1.25	1.18	1.14		1.11	1.07	1.05		1.04			1.03	1.02
	1/4 full	1.33	1.27	1.23	1.20	1.16	1.14			1.13			1.12	1.11
	1/2 full	1.64	1.57	1.54	1.50	1.46	1.44			1.43			1.42	1.39
100.	empty	0.37	0.35	0.34	0.34	0.33	0.32			0.32			0.32	0.31
	1/4 full	0.40	0.38	0.37	0.36	0.35	0.35			0.35			0.34	0.34
	1/2 full	0.49	0.47	0.46	0.45	0.44	0.44			0.44			0.43	0.43

P = Percent of applied water that is deep percolation

F = interval between irrigations

However, in some cases, significant lateral flow of subsurface water can occur from adjacent or upperlying levels. Generally, the volume of lateral flow will be unknown.

Once the hydraulic conductivity, volume of drain water, depth of the water table at the midpoint between the drains, and depth of the drains are known, the spacing can be calculated using an appropriate method. The nomograph [22] shown in Figure 8-5 is commonly used for the San Joaquin Valley and was developed from drainage discharge and water table depth measurements of existing drainage systems. The procedure consists of first calculating the ratio of the drain discharge, q, over the hydraulic conductivity, K (note that the same dimensions must be used for both terms), and then locating q/K along the vertical axis. One then proceeds horizontally until the line representing the desired water table height above the drain, m, is intersected. (The value m is the difference between the depth of the drain and the depth of the water table at the midpoint between drains.) A vertical line is then drawn through the point of intersection down to the horizontal azis. The intersect of the vertical line with the horizontal axis gives the desired spacing. The procedure is illustrated in Figure 8-5. References in Table 8-9 provide more detailed procedures to other design methods.

If significant lateral inflow is believed to occur, then the spacing should be decreased somewhat to adjust for this additional flow. However, this adjustment is done by trial and error. If, after drain systems are installed, the water table depths at the midpoint are not adequate, it may be necessary to install additional drains by splitting the spacing.

Operation Plan

In addition to the construction plans and documents, the design engineer should provide an operation plan for use by the system operator. The plan should contain the following information.

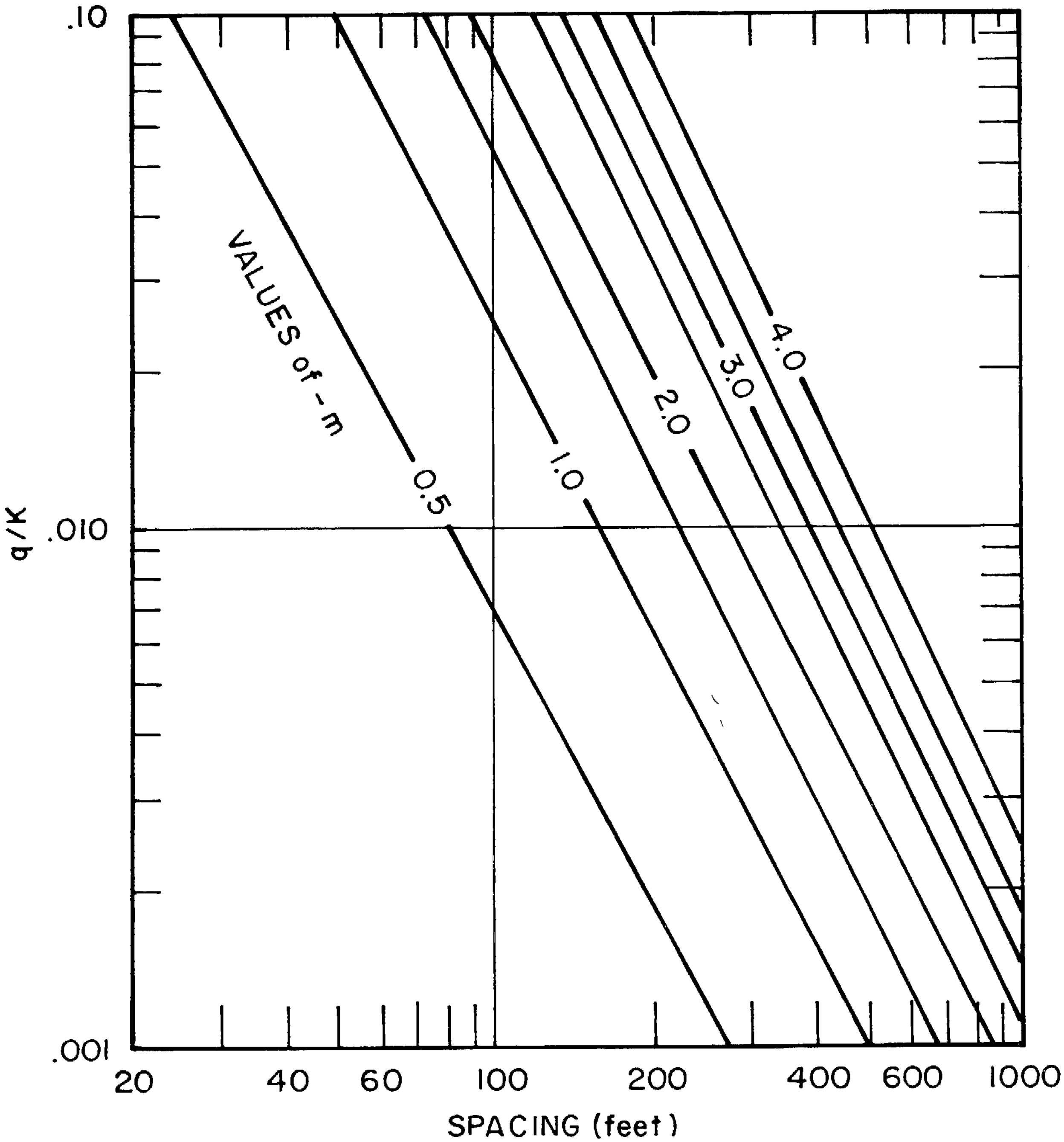

Figure 8-5. Nomograph used for determining drain spacings in the San Joaquin Valley

1. A layout map of the irrigated area showing:
   a. field or plot numbers, area, and crop
   b. irrigation system layout and controls
   c. drainage system layout and controls
   d. other pertinent information
2. Soil profile information showing:
   a. Textural changes with depth
   b. Available water capacity (AWC)
   c. Management-allowed deficiency before irrigation is scheduled (MAD)
3. Crop information:
   a. how to establish the crop
   b. crop rotations if necessary
   c. rooting depth
   d. critical growth periods
4. Irrigation water to be used
   a. source (wastewater or blend)
   b. irrigation-water-quality constituents
   c. flow rates and time available
   d. operating pressure
   e. how to control flow or pressure
5. How to schedule irrigations
6. How to tell when to stop irrigation
7. How many fields can be irrigated at the same time
8. Which fields should be irrigated first, second, etc.
9. Sequence to follow in starting the irrigation system
10. Sequence to follow in stopping the irrigation system
11. Safety checks
12. Maintenance procedures and frequency
13. Monitoring schedule required by regulatory agencies or for crop management
14. As-built plans of the system

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CHAPTER 9

ON-FARM ECONOMICS OF RECLAIMED WASTEWATER IRRIGATION

Charles V. Moore, Kent D. Olson and Miguel A. Mariño

INTRODUCTION

For irrigation with reclaimed wastewater to be a reasonable alternative for municipalities, financial and economic feasibility for farm owners-operators, landowners, and farm tenants must be shown. Financial and economic feasibility are important to both the farmer and the municipality. In the case where a municipality owns the land, the project must be attractive to potential tenants: landowners/farm operators must be better off contracting for the water rather than doing without. But this chapter focuses only on the farmer's view.

In this chapter, we will first briefly describe the supply characteristics of treated wastewater with respect to seasonality of flows (with and without storage), transportation costs, and pricing considerations. Next we will characterize the components making up economic demand for treated wastewater, including monthly evapotranspiration of adoptable crops, alternative application methods, nutrient value of primary and secondary treated wastewater, and salinity problems, and will make some general comments on risk and uncertainty. Finally, we will look at the treatment-disposal system as a whole using a linear programming model of an individual farm to indicate the sensitivity of a profit-maximizing farm operator to variations in the supply-and-demand characteristics and contractual arrangements of reclaimed wastewater.

SUPPLY CHARACTERISTICS OF TREATED WASTEWATER

Seasonal Variations in Wastewater Flows

Seasonal variations in wastewater flows occur in communities with seasonal commercial and industrial activities [1]. The seasonal fluctuation of population, such as students and tourists, also results in an extreme variation in wastewater flows. See Chapter 2 for additional detail on seasonal variation.

Figure 9-1 shows the monthly pattern of inflows to the municipal wastewater treatment plant at Davis, California, a city of approximately 35,000 people with no major water-using industry. The single large food-processing plant in the city has its own treatment facilities, as does the University of California.

Conveyance Systems Costs

The total transportation cost to a reuse site will depend heavily on the distance from the treatment plant and the lift, if any, to move the treated wastewater to an area where soils and topography are conducive to irrigated farming.

Construction costs vary from one geographical area to another as well as within the same area, depending upon the particular construction condition encountered (e.g., open-land versus in-city construction). Construction costs also vary according to the size and material of pipe used, appurtenances, construction depth, pumping requirements, etc. For example, a typical construction cost curve, in 1978 dollars as a function of capacity, is given in Ocanas and Mays [2]. It is based on data collected by Dames and Moore [3] such that:

$$\text{Pipe construction cost (\$/ft)} = 80.0\ Q^{0.461} \qquad [9\text{-}1]$$

in which Q is the design capacity in millions of gallons per day (MGD). Construction bid costs were collected by Dames and Moore [3] for over 500 sanitary sewer pumping stations ranging in capacity from 0.1 MGD (380 m^3/day) to over 100 MGD and with pumping heads from 10 ft to over 100 ft. This survey led to the following cost equation:

$$\text{Pumping station cost (\$/ft of head)} = 1.33 \times 10^5\ Q^{1.08} \qquad [9\text{-}2]$$

in which Q is the design capacity in MGD.

Off-Line Storage

Design factors for the reclaimed wastewater storage capacity required in land application systems include length of the nonapplication season, wastewater flow, precipitation, evaporation, and seepage [4]. Based on climate and weather variations, computer programs have been developed by the U.S. Environmental Protection Agency (EPA) [5] that enable the estimation of storage requirements for all portions of the United States. For example, the average

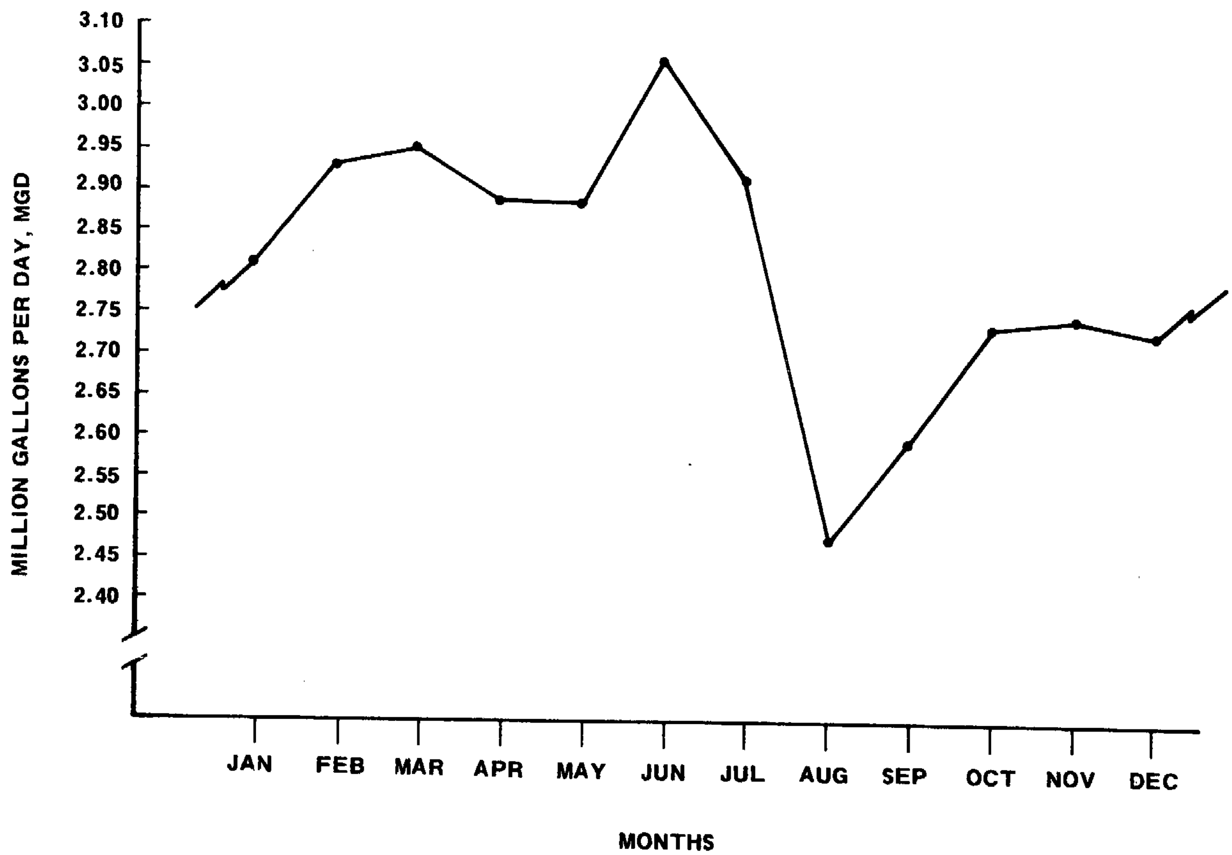

Figure 9-1. Daily inflows by month to the municipal wastewater treatment plant at Davis, California, 1973-81.

number of nonapplication days for which storage would normally be required in Sacramento is about 40 days.

Most agricultural reservoirs are constructed with earth embankments of uniform materials [6]. In California, any reservoir with embankments higher than 6 ft (1.8 m) and a capacity in excess of 50 acre-ft (61,600 m^3) is subject to state regulations on design and construction of dams, and plans must be reviewed and approved by the appropriate agency [7].

Figure 9-2 shows capital and annual costs vs. storage volume. For a storage volume of 1 MG, the capital outlay is expected to be about $5,000 (in 1979 dollars). In addition, one may require reservoir lining and embankment protection. There are significant economies of size in operation and maintenance costs, as indicated in Fig. 9-2b. These costs are based on idealized data: Reed et al. [8] give additional information on data development.

Depending on the contractual arrangements between the municipality and the landowner, the cost of storing wastewater may be paid by the city, by the landowner, or by both. Storage costs can be quite significant and must be taken into account in determining the economic feasibility of utilizing reclaimed wastewater. The importance and impact of off-line storage for farm operators utilizing treated wastewater will be clarified in the discussion on matching supply and demand for water in a later section entitled "Putting It All Together".

Pricing Considerations

The municipalities' objective in pricing reclaimed wastewater would be to minimize the cost of disposing of a fixed quantity of wastewater subject to water quality standards. If these standards for disposal into a water course require tertiary treatment, costs may be minimized by giving away the water to avoid the expense of meeting these stringent standards. However, the demand for irrigation water may be great enough to allow the municipality to recover all treatment, transportation, and storage costs through sales to farm operators.

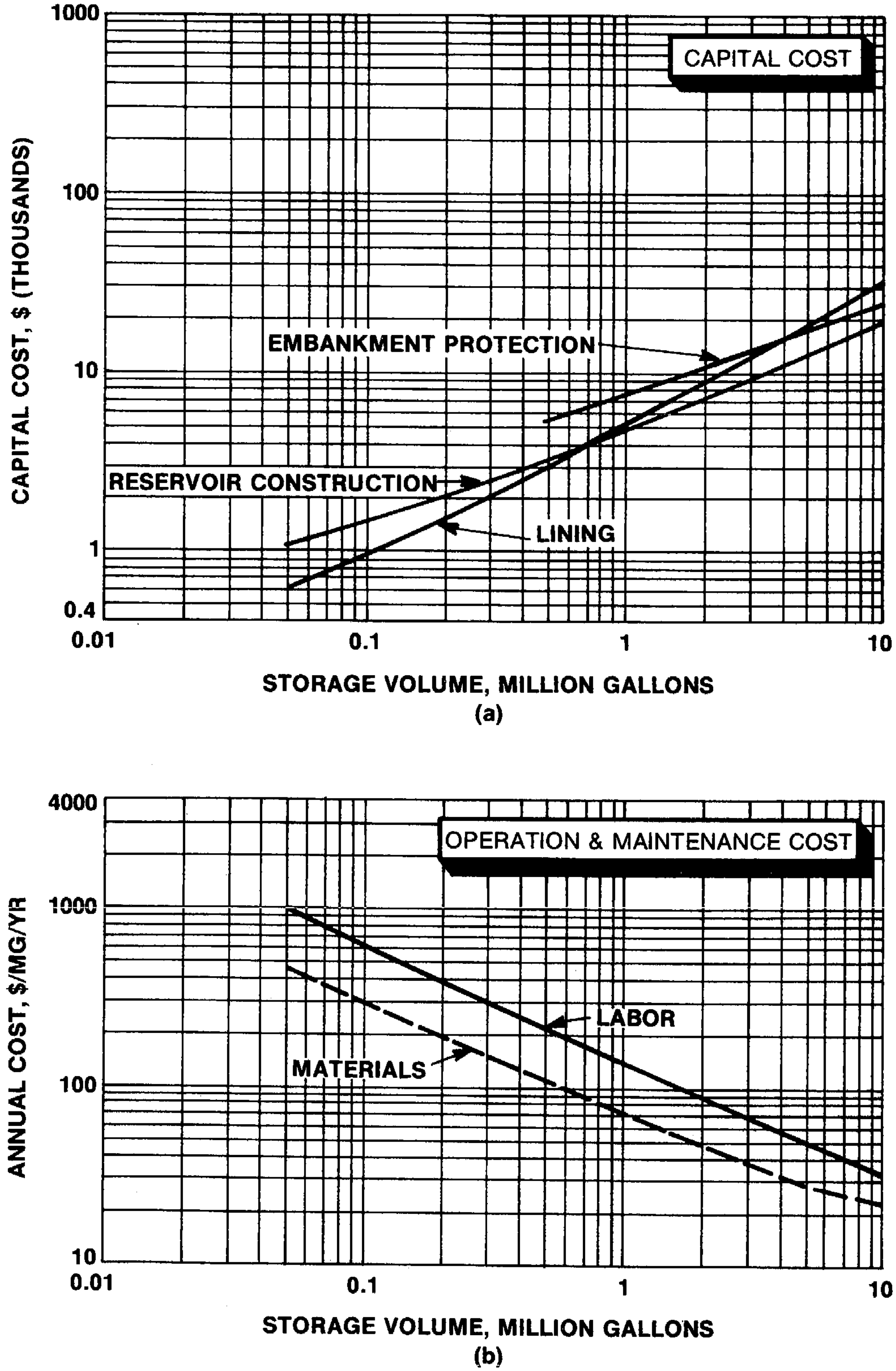

Figure 9-2. Cost curves for storage reservoir in 1979 dollars [8].

Landowners/farm operators, on the other hand, would have profit maximization as their economic goal, and their decision to purchase or accept treated wastewater will be based on the quantity, timing, quality, and cost of treated wastewater.

The final contract price will be negotiated considering all of these variables and factors. If, for example, water-quality standards require that effluent be usable for water contact sports and this level of treatment costs $133 per acre-ft or $0.41 per 1,000 gal ($0.11/m^3), the municipality would be better off subsidizing the cost of water to farmers up to $133 per acre-ft rather than paying to treat the wastewater. In fact, farm operators may be willing to pay for secondary treated water, thus decreasing the municipality's net cost of treatment.

The order of magnitude of treatment costs for various uses are shown in Table 9-1. These costs (1974 dollars) for water reuse have been adapted from Middleton [9] for 10 MGD (37.8×10^3 m^3/day) treatment systems. (The costs given are examples and do not apply to any specific local situation.)

System Reliability

The Wastewater Reclamation Criteria are contained in Title 22, Division 4, Sections 60301-60357 of the California Administrative Code (see Appendix F) and are discussed in Chapter 10 of this manual. A recent survey on wastewater reclamation facilities was conducted by the California State Department of Health Services in 1977-78 [10]. The survey revealed that 72% (176 out of 243) of the wastewater reclamation plants provided higher treatment than required for the intended use.

DEMAND CHARACTERISTICS OF IRRIGATION WATER

Seasonal and Daily Patterns of Demand and Transportation

Crops need different amounts of water at different seasons of the year. In California, summer months are high-demand months for irrigation water, while winter months have more rainfall and cooler weather. (Year-to-year fluctuations in evapotranspiration (ET) may vary widely from the long-term average, so the quantity of water

Table 9-1. Treatment costs by type of use (1974 dollars) [9].

Water reuse	Capital cost ($1,000)	Total operating cost (cent/1,000 gal)	Dollars per acre-ft
Irrigation	a	a	a
Recreation	9,641	40.7	132
Industrial	8,237	35.6	116
Domestic:			
Nonpotable	6,302	24.3	80
Near potable	12,357	62.2	202

a. Depends on water quality requirements for irrigation.

required for a specific crop will vary also.) The amounts of evaporation and transpiration have been quantified for types of crops and by geographical area. The ET rate varies with the amount of leaf area, temperature, wind, and other climatic conditions. Chapter 5 gives further details on ET data.

ET rates can be used to estimate the demand for water. However, oversupply of water can be just as detrimental as an undersupply. In low-demand months, alternative storage or disposal methods will probably be needed for excess water not required by crops.

This variation in demand may cause a variation in the pricing of water. Water in the summer is worth more, because the demand is greater. Water in the winter is worth less, because farmers may have no need for water--they may even have an oversupply in rainy years. There may be a need to pay farmers for disposal in the low-use months; however, farmers may be willing to pay for reclaimed wastewater in the high-use months. Using farm land for wastewater disposal in the low-use months may preclude the growing of crops in other months if disposal overlaps with planting and/or harvesting periods.

Potentially Adaptable Crops

Depending on the level of treatment by the municipality before delivery to the farm, it is possible to irrigate virtually any crop with reclaimed municipal wastewater. Thus, it is very important for the farm operator to have a clear understanding of reclaimed-wastewater-quality characteristics before contracting for it. For a detailed discussion of water-quality characteristics and their effects on crop selection, further reading in Chapters 2, 3, and 10 is recommended.

Limitations Due to Health Concerns

Reclaimed wastewater that has been oxidized, coagulated, clarified, filtered, and disinfected, can be used to irrigate a wide variety of crops. If the coliform count is below 2.2/100 mL, tertiary-treated wastewater can be used to irrigate food and vegetable crops, even under sprinkler irrigation. In other words, it can be used for any purpose that a farm operator would normally use irrigation water supplied from underground or district water sources. However, if this water is priced at the cost to the municipality, it can be expected to be relatively expensive.

Use of secondary treated effluent somewhat limits the types of crops that can be grown. If the effluent is oxidized and disinfected and the coliform count is not below 2.2/100 mL, the secondary treated wastewater can be applied to irrigated pasture for dairy animals but not to food crops.

Primary effluent use is limited to nonfood crops such as forages, fiber, and seed crops; however, it may be used in orchards and vineyards if the treated wastewater is applied by surface-irrigation methods. Additional detailed treatment requirements can be found in the Wastewater Reclamation Criteria, California Administrative Code Title 22, Division 4, Environmental Health, 1978 (see Appendix F) and also are discussed in Chapter 10.

Limitations Due to Climate

Climatic conditions affect the demand for irrigation water (and thus reclaimed wastewater) in two ways. First, short-growing-season areas limit the choice of crops available to the farm operator. In most cases, high-elevation areas will be limited to irrigated pasture, forages, and winter grain crops. The shorter growing season also implies lower total plant evapotranspiration and thus lower total water use per acre.

Second, even for areas with longer growing seasons (225 days or more), the demand for irrigation water can vary owing to changes in average daily temperature and wind speed. Thus, a forage crop grown in the desert area of southern California will consume significantly more water both in the peak months and in seasonal totals than the same crop grown in the Sacramento Valley. All other things being equal, the additional yield due to the longer growing season in southern California would enhance that region's ability to pay for water over that of an area with a shorter growing season.

Limitations Due to Soils

Information presented in Chapter 4 of this manual provides details on the hydraulic conductivity of soils. In general, the concentration of dissolved solids in treated wastewater will be higher, perhaps by 300 mg/L, than that of the municipal supply (see also Chapter 2). Drainage of a specific soil, either natural or artificial, will affect the ability of salts to move through the root zone. Low-salt tolerant crops will be difficult to germinate and will fail to produce satisfactory yields on these soils without careful irrigation management. In some cases, production may be economically infeasible.

Market Considerations

Most field and forage crops are grown widely throughout the United States, and thus access to a market is no problem. However, for many of California's specialty crops, a production or marketing contract is almost a necessity. The financial risk of not having a "home" for perishable crops at harvest time may be too great for some farms. Processing tomatoes and sugar beets, although grown widely in California, require a production contract with a processor. Thus because of contract necessity, a grower may not be able to change the crop mix quickly to use treated wastewater for irrigation. That is, the production, harvesting, and marketing schedules may not be flexible enough to allow for irrigation (i.e., disposal) of municipal wastewater during all periods.

Less perishable crops, such as wheat, pasture, or corn, may be more suitable for wastewater irrigation, because the market usually does not require marketing contracts and the grower has more flexiblity. Thus, these crops can adjust to the schedule of wastewater irrigation more readily than perishable commodities.

Distribution and Application Methods

Irrigation distribution systems generally fall into two broad categories: surface and sprinkler. A large number of combinations exist within these categories. In choosing the least-cost combination from the wide range of technologies available, the farm operator must have a knowledge of labor wage rates, water costs, interest rates, and power charges over time as well as of the soils, adaptable crops, and climatic conditions for the disposal-site farm.

This manual cannot cover all of the possible irrigation methods but can suggest broad guidelines for the planner. As the cost of water supplies increases in relation to wages and interest rates, additional capital can be invested profitably in water-conserving technologies. For example, under surface irrigation, as water costs increase, funds could be invested in reducing water losses by using pipelines, tailwater systems, laser leveling, and shorter lengths of runs.

Sprinkler systems tend to have similar irrigation application efficiencies so that system selection is heavily weighted toward those that reduce irrigation labor and have lower amortization and operating cost. Topography may dictate that sprinklers provide the only feasible method of irrigating a certain parcel. However, in deciding to irrigate or not to irrigate, the following factors should be kept in mind:

1. One pound of pressure per square inch (6.9 kPa) at the nozzle is equivalent to 2.31 ft (0.704 m) of head. Thus a 60-lb/inch^2 sprinkler is equivalent to 138.6 ft of lift. A 70-lb/inch^2 requirement would be equivalent to 161.7 feet of head.
2. In 1982, the electrical energy cost for pumping in California was about $0.11 to $0.12 per acre-ft per ft of lift. Thus, the cost of pressurizing a sprinkler system would range from $15.25 to $16.63 per acre-ft ($12.16 to $13.38/1000 m^3). These costs are projected to increase from 2% to 3% faster than the general inflation rate in the next few years.
3. The benefits of water conservation need to be evaluated as well as the costs of obtaining those benefits.

In choosing between surface irrigation methods and sprinklers, all other things being equal, significantly lower irrigation efficiencies and higher labor costs can be tolerated for surface irrigation before increasing water cost causes sprinklers to become cost-effective. A least-cost irrigation system should be selected only after considering all of these factors and the unique characteristics of the fields to be irrigated.

Alternative Irrigation Methods

Although the use of drip irrigation (with fresh water) is increasing, this section will not discuss drip irrigation with treated wastewater, because such experience in California is extremely limited.

Sprinkler System

The decision to use sprinkler or surface methods for applying irrigation water is not simple or trivial. Except for the requirements due to health concerns discussed earlier, the choice should be made on the same basis as if normal water sources were involved.

Sprinklers may be indicated when topography or nonuniform soil types make surface irrigation impossible. Other advantages of sprinklers might include better salt management, more uniform, light irrigations, and temperature and humidity control. Disadvantages might include high initial investment, amortization, and operating costs. With the rapid increase in energy costs, serious consideration should be given to the power costs of pressurizing and operating a sprinkler system in the future. In addition, the irrigator must consider the fixed costs of interest and depreciation along with repair and maintenance costs.

There appears to be no unique advantages with respect to type of sprinkler system, i.e., hand move, wheel roll, solid set, center pivot, etc., when utilizing treated wastewater. Thus, the choice of system must be based on economic and other considerations. However, care must be taken to position sprinklers or use shields so that wastewater does not drift onto adjacent property.

Surface System

Except for the limitations due to health concerns discussed earlier, use of treated wastewater for irrigation should have little effect on the choice of a surface distribution system. The most important consideration is to select the most cost-effective distribution system, given the price of water, labor wage rate, and interest rates. The higher the price (cost) of treated wastewater at the farm headgate, the greater the financial feasibility of investing in water-conserving devices and practices such as pipelines, gated pipe, laser leveling, and shortened length of runs.

Return Flow Systems

Regardless of whether a sprinkler or surface system is selected, a return flow or tailwater recovery system may be required under certain conditions. County health departments and/or regional water quality control boards may prohibit tailwater from leaving the field to enter drains or water courses. This prohibition may be imposed when primary or secondary treated wastewater is used, especially when excess water is applied over and above crop consumptive use in order to "dispose" of surplus water. If the farm headgate cost of treated wastewater is relatively high, a tailwater recovery system may be a cost-effective water conservation practice.

Value of Nutrients in Treated Wastewater

Plant nutrients are subject to the laws of diminishing returns just like any other variable input. For example, Figure 9-3 shows the results of a Sonoma County field trial comparing secondary treated wastewater containing 46 lb of N, 87 lb of P, and 43 lb of K per acre-ft (16.9 mg/L N, 32.0 mg/L P, 15.8 mg/L K) against fresh water from the municipal water supply. Diminishing returns to nitrogen are shown both for dry-weight and fresh-weight yields of the corn silage.

Placing a value on plant nutrients in treated wastewater is more difficult. However, some things can be inferred from data such as these. First, in this experiment, little additional production is generated after 50 lb of additional N is applied per acre, and after application of 75 lb N per acre, total yield starts to decline. Thus, if the nitrogen were free, a farm operator could profitably apply 75 lb of N per acre. However, if the nutrients were assigned their market value if purchased as commercial fertilizer, the optimum level of application would be less than 75 lb per acre.

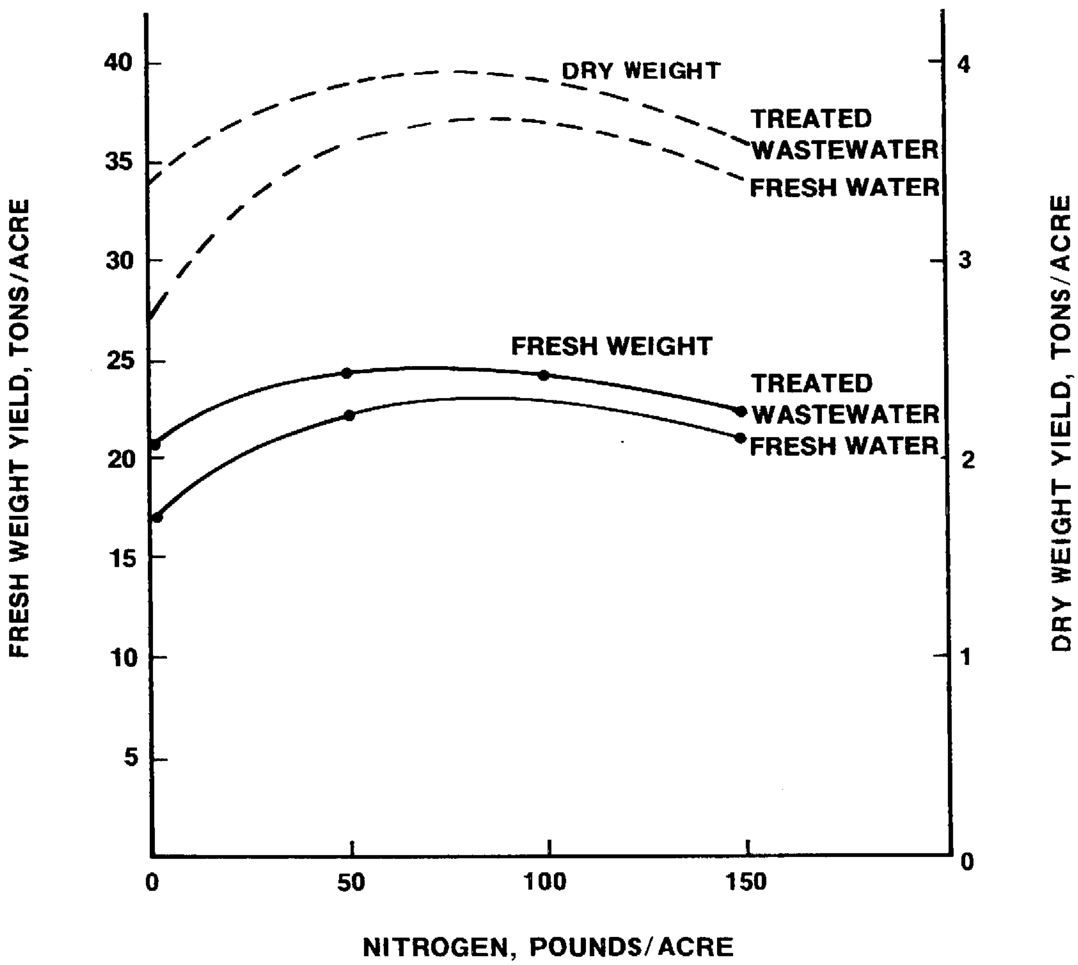

Figure 9-3. Corn silage yield response to nitrogen in Sonoma County, California, 1975.

In general, depending on the crop under consideration and the shape of the dose-yield response curve, the value of the nutrient content increases up to where the nutrient exceeds the level that causes yields to decline; its value then becomes zero or negative. That is, if the wastewater in the above example contains 46 lb of N per acre-ft and 3 acre-ft (3700 m^3) are applied, then the value of N in the last acre-ft would be zero or even negative. If for example, a primary treated wastewater contained approximately 100 lb of N per acre-ft, much of the nutrient content could be wasted if not blended with water supplies from fresh water sources. If a treated wastewater contained only 50 lb of N per acre-ft it would more nearly match nutrient supply with plant requirements, except on certain crops, such as sugar beets and processing tomatoes, where timing of nutrient availability is somewhat more critical.

An alternative method of valuing nutrients is the market approach. If farm managers choose not to use reclaimed wastewater, then plant nutrients must be purchased from the market. Table 9-2 provides prices paid by farmers per pound of actual nutrient as of March 15, 1981. Thus, for example, if a source of reclaimed municipal wastewater contained 0.23 lb of N per 1,000 gal (81.2 lb/acre-ft or 30 mg/L) the water would have a market equivalent of $12.83 per acre-ft in terms of the alternative cost of purchasing anhydrous ammonia. However, if the crop cannot utilize all of the nutrients, the unused portion has a zero value.

Salts in Reclaimed Wastewater

The salts in municipal wastewater may cause more water to be required to leach any salts that accumulate in the soil. The leaching fraction (LF) is the fraction of the total amount of applied water that drains below the root zone. The method of calculating the required LF is discussed in Chapter 7. If the water is very saline or the crop is salt-sensitive, the required leaching fraction may be fairly high, thus increasing the cost of irrigation substantially. For example, if the LF must be increased from 0.10 to 0.25, the energy cost of sprinkling will increase 20% [=(.25-.10)/(1-.25)].

Table 9-2. Prices paid by farmers for actual plant nutrient [11].

Fertilizer	Analysis (%)	Price per pound of nutrient N or P_2O_5 (\$)
Nitrogen		
Ammonium sulfate	20	0.375
Ammonium nitrate	33	0.315
Urea	45	0.282
Anhydrous ammonia	83	0.171
32% Nitrogen solution	32	0.303
Phosphorus		
Superphosphate	20	0.340
Triple superphosphate	45	0.296

In areas of high winter rainfall or where wastewater is blended with higher-quality water sources, leaching requirements will be reduced. Some areas may have groundwater that is saltier than the wastewater; using wastewater would reduce the required leaching over that required if the groundwater was used for irrigation.

The long-term accumulation of salts in the soil can lead to a decrease in the choice of crops to be grown. Chapters 3 and 7 discuss the sensitivity of crops to salt in more detail. Most fruit, nut, and vegetable crops and some field and forage crops are particularly sensitive to salt. A farmer will lose the ability to grow these high-value crops if salt builds up over time. Also, yields will decline for the remaining potential crops.

If the choice of crops decreases and the yield decreases because of salt buildup, the farmer will experience a decline in annual income and a loss in asset value, and the value of the land for agricultural use will decline.

The Effect of Risk and Uncertainty

The choice of whether to use wastewater for irrigation involves risk and uncertainty. Is there a need for a back-up water supply? What are the effects on landowner-tenant agreements? Does variation in crop price and yield affect a farmer's decision? Although risk and uncertainty can be positive in the sense of greater profits, managers usually are more concerned with "downside risk" (i.e., the risk of failure). This section discusses the effects of wastewater utilization on downside risk.

Depending on the reliability of wastewater treatment systems, a farmer may feel the need for a back-up supply of water. The supply of wastewater may or may not be constant. If the supply of wastewater is not constant, the farmer will need another supply of water to cover the needs during periods of wastewater shortfall. Even if the supply is constant, the farmer may need to have reserve well and pump capacity to meet the ET requirements for unpredictable periods of interruption of reclaimed wastewater supply. In either case, the value of the reclaimed wastewater is reduced because of the cost of having a back-up source. Even if the farmer does not have a back-up source, the value of the wastewater is reduced because of the potential loss in income due to plants being put under stress. Stress may occur as a result of the interruption of supply and/or a nonconstant supply of reclaimed wastewater.

By the same reasoning, too much water reduces the value of wastewater. If the contract requires the farmer to dispose of all water from the treatment plant, farm productivity may be negative in some months or on some fields.

The final agreement between landowner and tenant depends upon several factors. An important factor is the amount of risk that is shared between the two parties. This has an indirect effect on the potential use of reclaimed wastewater. With cash rent, the landowner receives a fixed, known income from the land, and the tenant has a considerable amount of freedom in crop selection and how the land is farmed. With a crop-share lease, the landowner receives a larger share of the expected income in return for being willing to share in any loss that may occur. Because the landowner has some uncertainty about his/her income, the landowner will usually participate in more management decisions. Usually the landowner will press for those crops that give the largest return to land, whereas the tenant will press for those crops that give the largest return to his/her management, labor, and capital. These "votes" will not always be for the same crops. The landowner's desires usually limit the crop choices for the tenant. This limiting of choice may reduce the tenant's ability to adapt to the supply and characteristics of reclaimed wastewater for irrigation. In the case where the land is owned by the municipality and not a profit-maximizing landlord, a different set of objectives and constraints will have to be reconciled. For instance, the municipality may have the disposal of all treated wastewater as a primary goal. These conflicts are explored further in the next section.

A very large portion of risk and uncertainty is the variability of crop prices and yields. This variability affects the expected return of different crops. A farmer chooses a crop based in part on the expected income of that crop, the variation in the expected income, and the farmer's ability and willingness to manage that variation. This decision process affects the use of wastewater by potentially removing from consideration a crop or crops that may be useful in adapting to wastewater irrigation. The effect of income variations varies with individual farmers; thus no generalities can be drawn, except that this may restrict the potential adoption of wastewater for irrigation.

PUTTING IT ALL TOGETHER

Linear programming (LP) is a mathematical technique for optimizing an objective by selecting activities or options (crops, livestock, feeds, for example) which compete for limited resources (land, capital, time, for example) or meet other constraints (nutrient requirements, for example). One major use of linear programming in agriculture is maximizing profits by selecting the optimal mix of crops with land, capital, machinery, and time as limited resources.

Linear programming can assist in making decisions for efficient resource allocation among activities and options. LP allows for the simultaneous consideration of many constraints. LP allows the user to answer many "What if..." questions in a quick, orderly fashion.

Linear programming is used to illustrate the trade-offs involved in utilizing reclaimed wastewater in agriculture production. An example of using LP to evaluate the choice of using wastewater is applied to a typical farm in Yolo County, Calif., and the municipal wastewater flow from the city of Davis. The daily flows of Davis wastewater are given in Figure 9-1. Average annual inflow is 1,016 million gallons, and the nitrogen level in the primary effluent is 31.656 mg/L (0.264 lb/1000 gal). These data do not include wastewater from the University of California at Davis or the wastewater from the Hunt-Wesson canning plant. Wastewater from these latter two sources are treated by their own facilities.

A Description of the Model

The LP model maximizes income by choosing crops that allow the constraints to be met. The potential crops are selected on the basis of physical feasibility--in Yolo County in this example. The price, yield, and cost information is included in Table 9-3. The options of

Table 9-3. Prices, yields, costs, and other parameters used in the LP model.

	Wheat	Barley	Corn	Alfalfa	Irrigated pasture	Sugar beets	Tomatoes
Price, $	7	6	7	80	100	25	56.5
Yield per acre	55	50	90	7	1	28	25
Units	cwt	cwt	cwt	ton	acre	ton	ton
Variable cost excluding water and nitrogen costs	91.48	76.57	227.55	176.82	8.6	579.49	670.16
Return over Adj. Var. Costs	293.52	223.43	402.45	383.18	91.4	120.51	742.34
Water Requirements: (1000 gallons/acre)							
January	0	0	0	0	0	0	0
February	13	13	0	1	0	0	0
March	105	105	0	72	72	0	0
April	203	203	0	158	162	74	28
May	277	277	47	231	235	256	98
June	189	189	197	293	297	352	293
July	0	0	389	322	330	389	384
August	0	0	330	275	284	344	263
September	0	0	173	211	215	240	0
October	0	0	0	130	130	143	0
November	0	0	0	35	30	0	0
December	0	0	0	0	0	0	0
Nitrogen required: (lbs, @ $.20/lb)	80	80	200	0	200	125	100

pumping fresh water or using reclaimed wastewater are included. The supply of wastewater is determined for each month. There is some nitrogen available in wastewater; if the crop's need is not met from wastewater, nitrogen can be purchased.

Several cases are evaluated to analyze different conditions that may occur on farms. The changes involve whether the farm has a limited or unlimited acreage, whether the reclaimed wastewater may be blended with fresh water, whether primary or secondary effluent is used, whether all the wastewater must be used on the farm, and at what price of reclaimed wastewater the farmer chooses not to use wastewater. The cases are defined below:

Case I. Maximum size is 350 acres. Primary effluent is used, and blending with fresh water (at $16.00/ acre-ft or $0.49/1,000 gal) is allowed. This includes the more likely situation where the total supply of effluent does not need to be used on the farm. No off-line storage is allowed.

Case II. Acreage is unlimited. Only primary effluent is available; blending with fresh water is not allowed. The total supply of effluent does not need to be used on the farm. No off-line storage is allowed.

Case III. Maximum size is 350 acres. Secondary effluent is used, and blending with fresh water is allowed. The total supply of effluent does not need to be used on the farm.

Case IV. Acreage is unlimited. Only secondary effluent is available; blending with fresh water is not allowed. The total supply of effluent must be used on the farm. No off-line storage is allowed.

The results of these cases are reported in the following section.

Summary of Results

Table 9-4 summarizes the results of the LP models, excluding Case IV. Overall, we note that no case uses all available effluent. The crops do not need to be irrigated in winter, and they need less

Table 9-4. Summary of crop acreages, water use and surplus, and nitrogen oversupply in all cases.

Item	Case I		Case II		Case III	
Effluent price range ($ per 1,000 gal)	.01-.02	.025-.045	.01-.03	.01-.02	.025-.035	.04-.045
Crop acreages						
Wheat	0	0	173	0	0	0
Corn	138	245	111	204	216	238
Alfalfa	107	0	0	41	29	7
Tomatoes	105	105	122	105	105	105
Totals	350	350	406	350	350	350
Reclaimed wastewater (1,000 gal)[a]						
Used	390,219	313,609	393,086	342,878	334,299	318,584
Oversupply	626,291	702,901	623,424	673,632	682,211	697,926
Fresh-water use (1,000 gal)	63,497	76,512	0	71,539	72,996	75,667
Nitrogen oversupply (lb/acre)						
Wheat	0	0	205	0	0	0
Corn	137	138	137	24	24	24
Alfalfa	455	0	0	216	216	216
Tomatoes	89	89	248	39	39	39

a. To convert to acre-ft, divide values (in 1,000 gal) by 325.85

water during the early and late part of the growing season. The models do not allow off-line storage; if this were possible, the farm may be able to better utilize the entire wastewater supply. The two main crops chosen are corn and tomatoes; wheat and alfalfa are chosen as conditions and prices vary.

Case I. 350-acre farm, primary effluent, blending with fresh water is allowed but no storage is allowed.

The price for effluent is varied from $.01/1,000 gal ($3.25/acre-ft) to $.045/1,000 gal ($14.55/acre-ft) in $.005 increments. The cropping pattern changes only once as the price increases. For $.01 to $.02 per 1,000 gal of effluent, the optimum crop mix consists of 138 acres of corn, 107 acres of alfalfa, and 105 acres of tomatoes. For $.025 through $.045 per 1,000 gal, the optimum mix is 245 acres of corn and 105 acres of tomatoes. The 350 acres are fully utilized with all prices.

The use of primary effluent decreases by 19.6% when the price reaches $.025 per 1,000 gal--from 1,198 acre-ft to 962 acre-ft (3.42 acre-ft/acre to 2.75 acre-ft/acre). This occurs at the same water cost where the cropping pattern changes. The unused primary effluent increases at this point--from 1,192 acre-ft to 2,157 acre-ft. The use of fresh water increases from 194 acre-ft to 234 acre-ft.

Surplus and non-utilized nitrogen above the required amount is 137 lbs N/acre-ft for corn, 455 lbs N/acre for alfalfa, and 89 lbs N/acre for tomatoes. As expected, farm gross receipts minus variable expenses declined from $114,732 to $102,943 as the price of primary effluent increased.

Overall water use is not very sensitive to changes in the price of water (Table 9-5).

Case II. Unlimited acreage, only primary effluent available, no fresh water allowed, and no storage is allowed.

Varying the effluent price results in no change in the cropping pattern. Fourteen different prices ranging from $.01/1,000 gal ($3.25/acre-ft) to $.30/1,000 gal ($97.74/acre-ft) are tried. The optimum cropping pattern consists of 173 acres of wheat, 111 acres of

Table 9-5. Monthly water use (1,000 gal) and surplus in Case I--primary effluent price range.

Month	$.01 to $.02 per 1,000 gal[a]			$.025 to $.045 per 1,000 gal		
	Primary effluent		Fresh-water use	Primary effluent		Fresh-water use
	Use	Surplus		Use	Surplus	
January	0	82,490	0	0	82,490	0
February	96	78,994	0	0	79,090	0
March	7,719	83,731	0	0	91,450	0
April	19,886	66,764	0	2,948	83,702	0
May	41,587	47,983	0	21,830	67,740	0
June	89,351	1,049	0	79,019	11,381	0
July	90,160	0	38,206	90,160	0	45,384
August	77,250	0	25,291	77,250	0	31,128
September	46,429	31,421	0	42,402	35,448	0
October	14,014	70,806	0	0	84,820	0
November	3,727	78,603	0	0	82,330	0
December	0	84,450	0	0	84,450	0
Total	390,219	626,291	63,497	313,609	702,901	76,512

a. To convert to acre-ft, divide values (in 1,000 gal) by 325.85

corn, and 122 acres of tomatoes for a total of 406 acres. Gross receipts minus variable costs ranged from $118,671 to $4,677 as the water cost increased.

Nitrogen above the required amounts is 205 lb N/acre for wheat, 137 lb N/acre for corn, and 228 lb N/acre for tomatoes. The total amount of primary effluent used at each price is a constant 1,206 acre-ft, leaving 1,913 acre-ft unused. Monthly water use is shown in Table 9-6.

Comparing this with Case I (where blending was allowed and included a maximum acreage of 350 acres), we observe a shift away from alfalfa hay to wheat. This causes a lower net income per acre, since wheat returns are lower than those for alfalfa. At an effluent price of $.01/1,000 gal ($3.25/ac-ft), gross receipts minus variable expenses of $114,723 are generated for 350 acres in Case I, or $328/acre, and $118,671 on the 406 acres in Case II, or $292/acre. Thus, expanding the land area to utilize all or nearly all of the effluent without the benefit of storage actually reduces net farm income per acre by $36 per acre.

Case III. 350-acre farm, secondary effluent, blending with fresh water is possible, but no storage is allowed.

Water price is varied from $.01/1,000 gal ($3.25/acre-ft) to $.045/1,000 gal ($14.66/acre-ft) in $.005 increments. The cropping pattern changes twice (though only slightly) as the price increases. For an effluent cost of $.01 to $.02 per 1,000/gal, 204 acres of corn, 41 acres of alfalfa, and 105 acres of tomatoes is the optimum crop mix. From $.025 to $.035, the optimum mix is 216 acres of corn, 29 acres of alfalfa, and 105 acres of tomatoes. Prices of $.04 and $.045 result in 238 acres of corn, 7 acres of alfalfa, and 105 acres of tomatoes as the optimum mix. The 350 acres are fully utilized at each price.

The quantity of effluent used decreases at prices of $0.25/1,000 gal ($81.25/acre-ft) and $.04/1000 gal ($13.05/acre-ft) from its original 1,052 acre-ft to 1,025 acre-ft and then to 977 acre-ft, for a total decrease of 7%. Thus, as the price of reclaimed wastewater

Table 9-6. Monthly water use and surplus (1,000 gal)[a] in Case II - Primary effluent price range.

Month	$.01 to $.30 per 1,000 gallons		
	Primary effluent		Fresh water
	Use	Surplus	Use
January	0	82,490	0
February	2,320	76,770	0
March	18,231	73,219	0
April	38,683	47,967	0
May	65,215	24,355	0
June	90,400	0	0
July	90,160	0	0
August	68,798	8,452	0
September	19,279	58,571	0
October	0	84,820	0
November	0	82,330	0
December	0	84,450	0
Total	393,086	623,424	0

a. To convert to acre-ft, divide values (in 1,000 gal) by 325.85

increases, there is a shift away from reclaimed wastewater to fresh water and a small shift in the cropping pattern. The nitrogen supply above the required levels is 24 lbs N/acre of corn, 216 lb N/acre of alfalfa, and 39 lb N/acre tomatoes. Monthly water use is shown in Table 9-7.

Major differences in cropping patterns are observed between this case (Case III) and Case I (using primary effluent instead of secondary). Under Case I, the optimum plan includes the same crops -- corn, alfalfa, and tomatoes--when the price of the primary effluent is between $.01 and $.02/1,000 gal but utilizes different acreages. In Case I, there are 138 acres of corn and 107 acres of alfalfa, but in Case III, over 200 acres of corn and less than 45 acres of alfalfa are planted. It appears that the shift in the crop mix is influenced, in part, by the economical supply of plant nutrients in the primary effluent.

Case I and Case III are similar in that when the price of the effluent increases (whether it is primary or secondary), there is a shift away from alfalfa to corn production.

Case IV is not reported in detail. Case IV is similar to Case III except that the farm acreage in Case IV is unlimited. Although the farm is unlimited in size, it is required to use all available effluent; the farm is physically unable to do this. This is due to two reasons. First, there are not many situations in California requiring irrigation water in December or January. Second, with no other water available except reclaimed wastewater a farm cannot balance the seasonal inequities in supply and demand. Off-line storage and/or land for disposal may enable the farm to take all the treated effluent, but both options will decrease farm income.

In this section, we have shown how a farm would optimize the use of available wastewater. Although these results cannot be applied to other geographical areas, they do show that a farm cannot be expected to take all wastewater without major managerial and operational changes. Over the range of prices considered, the results also show that a farmer would choose to use wastewater at the farm. These optimization models did not evaluate the construction of a distribution system from a treatment plant to a farm field.

Table 9-7. Monthly water use and surplus in Case III--Primary effluent price range.

Month	$.01 to $.02 per 1,000 gal[a]			$.025 to $.035 per 1,000 gal			$.04 to $0.45 per 1,000 gal		
	Primary effluent		Fresh-water	Primary effluent		Fresh-water	Primary effluent		Fresh-water
	Use	Surplus	use	Use	Surplus	use	Use	Surplus	use
January	0	82,490	0	0	82,490	0	0	82,490	0
February	37	79,053	0	26	79,064	0	6	79,084	0
March	2,949	88,501	0	2,084	89,366	0	501	90,949	0
April	9,419	77,231	0	7,523	79,127	0	4,048	82,602	0
May	29,378	60,192	0	27,166	62,404	0	23,113	66,457	0
June	82,966	7,434	0	81,809	8,591	0	79,690	10,710	0
July	90,160	0	42,641	90,160	0	43,445	90,160	0	44,918
August	77,250	0	28,898	77,250	0	29,551	77,250	0	30,749
September	43,941								
October	5,354	79,466	0	3,784	81,036	0	910	83,910	0
November	1,424	80,906	0	1,007	81,450	0	242	82,088	0
December	0	84,450	0	0	84,450	0	0	84,450	0
Total	342,878	673,632	71,539	334,299	682,211	72,996	318,584	697,926	75,667

a. To convert to acre-ft, divide values (in 1,000 gal) by 325.85

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CHAPTER 10

HEALTH AND REGULATORY CONSIDERATIONS

James Crook

INTRODUCTION

The State of California has long recognized the value of reusing wastewater and for many years has encouraged such reuse where public health is not compromised. Advances in wastewater treatment technology, including treatment reliability, allow the safe use of effluent for several purposes when reasonable precautions are taken.

The purpose of this chapter is (1) to summarize the health aspects of irrigation with reclaimed municipal wastewater, especially as related to pathogens, and (2) to describe the regulations in California that govern the reuse of treated wastewater.

HEALTH ASSESSMENT

Clearly, most wastewater reclamation and reuse operations impose a greater risk of public or worker exposure to pathogens or toxic substances than would the use of unpolluted waters of non-sewage origin. The objective, therefore, is to minimize the exposure and reduce the potential health hazards to acceptable levels. In general, the health concern is in proportion to the degree of human contact with the water, the quality of the effluent, and the reliability of the treatment processes.

The contaminants in reclaimed water that are of health significance may be grossly classified as biological and chemical agents. For most of the uses of reclaimed water, biological agents pose the greatest health risks, and quality standards are properly directed at these agents. Control of chemical contaminants is necessary for higher uses of reclaimed water, where the public is more directly exposed and ingestion of the reclaimed water or its constituents is more likely.

From a public health standpoint, the major chemical constituents of concern are the toxic heavy metals, pesticides, and other organic contaminants that may cause adverse long-term health effects. The mechanisms of food contamination include: physical contamination, where evaporation and repeated application may result in a build-up of contaminants on crops; uptake through the roots from the applied water or the soil; and foliar uptake. Groundwater contamination by chemical and biological constituents is discussed in Chapters 12 through 15.

While there is a paucity of information regarding the health significance of many of the known or suspected carcinogenic, mutagenic, or teratogenic organic constituents that may be present in wastewater used for crop irrigation, some chemical constituents are known to accumulate in particular crops and thus may present health hazards to both grazing animals and humans [1]. The chemical constituents of wastewater and the effect of treatment processes on them are discussed in Chapter 2. The effects of chemical constituents on plant growth and soils are discussed in Chapters 3 and 7, and the fate of metals and trace organics in the soil is covered in Chapters 13 and 15.

Types of Microorganisms

Properly operated state-of-the-art wastewater treatment plants can reduce pathogen concentrations by many orders of magnitude. However, it is difficult to assure complete, continuous elimination of pathogens, and the potential for disease transmission through water reuse has not been eliminated. In general, the disease organisms responsible for epidemics in the past are still present in today's sewage. Good sanitary engineering practice results in control rather than total eradication of the disease agent.

The numbers of pathogens in sewage have markedly declined over the decades as a result of disease control with antibiotics and improved sanitary conditions and practices. During an outbreak, pathogen numbers in local sewage go up, and it would be inappropriate to be careless simply because present pathogen densities may be relatively low. The principal infectious agents that may be present in raw sewage may be classified into three broad groups: bacteria, parasites (protozoa and helminths), and viruses. Table 10-1 summarizes the major infectious agents potentially present in raw domestic wastewater.

Table 10-1. Major pathogens potentially present in raw domestic wastewater.

Pathogen	Disease
Protozoa	
Entamoeba histolytica	Amebiasis (amebic dysentery)
Giardia lamblia	Giardiasis
Balantidium coli	Balantidiasis (dysentery)
Helminths	
Ascaris lumbricoides (Roundworm)	Ascariasis
Ancylostoma duodenale (Hookworm)	Ancylostomiasis
Necator americanus (Roundworm)	Necatoriasis
Ancylostoma (spp.) (Hookworm)	Cutaneous Larva Migrans
Strongyloides stercoralis (Threadworm)	Strongyloidiasis
Trichuris trichiura (Whipworm)	Trichuriasis
Taenia (spp.) (Tapeworm)	Taeniasis
Enterobius vermicularis (Pinworm)	Enterobiasis
Echinococcus granulosus (spp.) (Tapeworm)	Hydatidosis
Bacteria	
Shigella (4 spp.)	Shigellosis (dysentery)
Salmonella typhi	Typhoid fever
Salmonella (~1700 spp.)	Salmonellosis
Vibrio cholerae	Cholera
Escherichia coli (enteropathogenic)	Gastroenteritis
Yersinia enterocolitica	Yersiniosis
Leptospira (spp.)	Leptospirosis
Viruses	
Enteroviruses (71 types) (polio, echo, Coxsackie)	Gastroenteritis, heart Anomalies, meningitis, others
Hepatitis A virus	Infectious hepatitis
Adenovirus (31 types)	Respiratory disease
Rotavirus	Gastroenteritis
Parvovirus (2 types)	Gastroenteritis

Bacteria

One of the most common pathogens found in municipal wastewater is the bacteria of the genus *Salmonella*. This group contains a large number of species that can cause disease in humans and animals. There are three distinct forms of salmonellosis in humans: enteric fevers, septicemias, and acute gastroenteritis. The most severe enteric fever form of salmonellosis is the typhoid fever caused by *Salmonella typhi*. At one time, typhoid fever was so prevalent that death rates of more than 50 per 100,000 population were not uncommon in cities in the United States. Now, however, death due to this disease is practically nonexistent [2]. The most common form of *Salmonella* isolated from human sources in the United States is *Salmonella typhimurium*. Approximately 1500 serotypes are known, but only 200 or so different types are detected in any one year [3].

There are a variety of other bacteria of lesser importance that have been isolated from sewage. These include *Vibrio*, *Mycobacterium*, *Clostridium*, *Leptospira*, and *Yersinia* species. Although these pathogens may be present in wastewater, their concentrations are usually too low to initiate disease outbreaks.

Waterborne gastroenteritis of unknown cause is frequently reported, and the suspected agent is bacterial. One potential source of this disease is certain gram-negative bacteria normally considered nonpathogenic. These include enteropathogenic *Escherichia coli* and certain strains of *Pseudomonas*, which may affect the newborn [4]. Recently, *E. coli* has been implicated in outbreaks of travelers' diarrhea [5], probably through production of an endotoxin in the small intestine.

In recent years, *Campylobacter coli* has been identified as the cause of a form of bacterial diarrhea in humans. Although it has been well-established that this organism causes disease in animals, it has only recently been implicated as the etiologic agent in waterborne disease outbreaks. One of these outbreaks in the United States involved 2100 cases [1].

Parasites

There are a variety of protozoan and metazoan agents that are pathogenic to humans and that may be found in municipal wastewater. Probably the most serious of the parasites is the protozoan *Entamoeba histolytica*, which is responsible for amoebic dysentery and amoebic hepatitis. These diseases occur worldwide, although the incidence in the United States is not well-documented.

Another protozoan, the flagellate *Giardia lamblia,* is the cause of the disease giardiasis, which is responsible for gastrointestinal disturbances, flatulence, diarrhea, and discomfort and is emerging as a major waterborne disease. As is the case with *E. histolytica,* the cystic form of *G. lamblia* is the infective agent, and it also exhibits resistance to chlorine disinfection [6]. The number of outbreaks and cases of giardiasis has increased significantly in recent years [7], with one outbreak in 1974-75 affecting 4800 people in Rome, New York. At present, *Giardia* is the most common disease-causing intestinal parasite in the United States.

Several helminthic parasites may be found in wastewater. The most important are intestinal worms, including the stomach worm *Ascaris lumbricoides,* the tapeworm *Taenia saginata,* the whipworm *Trichuris trichiura,* the hookworms *Ancylostoma duodenale* and *Necator americanus*, and the threadworm *Strongyloides stercoralis*. Many of the helminths have complex life cycles, including a required stage in intermediate hosts. The infective stage of some helminths is either the adult organism or larva, whereas in other helminths the eggs or ova constitute the infective stage of the organisms. The eggs and larvae are resistant to environmental stresses and can be expected to survive usual wastewater disinfection procedures.

Viruses

Viruses are obligate intracellular parasites that are able to multiply only within a host cell. Enteric viruses are those that multiply in the intestinal tract and are released in the feces of infected persons. Over 100 different enteric viruses capable of producing infections or disease are excreted by humans.

The most important human enteric viruses are the enteroviruses (polio, echo, and Coxsackie), rotaviruses, reoviruses, parvoviruses, adenoviruses, and hepatitis A virus [6,8]. Hepatitis A, the virus causing infectious hepatitis, is the virus most frequently reported and documented to be transmitted by contaminated water. No host other than man has been found for the hepatitis virus. In spite of the inability to successfully cultivate the etiologic agent in the laboratory, there is irrefutable epidemiological evidence available to incriminate water as the vehicle of transmission of hepatitis A [9,10,11,12]. Several investigators have found viruses in groundwater, and groundwater has been implicated in several disease outbreaks of viral origin [13]. There have been many other viral disease outbreaks where water has been suspected as transmitting the viral agent; however, in most cases, the evidence has not been conclusive [14,15].

Although many incidents of waterborne transmission of viruses undoubtedly are not recognized, investigated, or reported, the available epidemiological data indicate that the role of water in the overall incidence of viral diseases may be limited [16,17,18] and that other modes of transmission, such as personal contact, probably are responsible for the great majority of viral diseases [19]. Even though water may not play an important role in the overall transmission of viral diseases, the potential public health significance of viruses in water should not be neglected or underestimated. Theoretically, any excreted virus capable of producing infection when ingested could be transmissible by inadequately treated wastewater [20].

Mechanisms of Disease Transmission

Disease can be transmitted to humans either directly by contact, ingestion, or inhalation of infectious agents in reclaimed water, or indirectly by contact with objects previously contaminated by the reclaimed water. The following circumstances must occur for a person to become ill: (1) the infectious agent must be present in the community producing the wastewater and, hence, in the wastewater from that community; (2) the agents must survive all the wastewater treatment processes to which they are exposed; (3) the person must either directly or indirectly come in contact with the effluent; and (4) the agents must be present in sufficient numbers at the time of contact to cause illness.

Contact with infectious agents does not always result in illness. Whether illness occurs depends on a series of complex interrelationships between the host and the infectious agent. Specific variables include the numbers of the invading microorganism (dose), the numbers of organisms necessary to initiate infection (infective dose), the organism's ability to cause disease (pathogenicity), the degree to which the microorganism can cause disease (virulence), and the relative susceptibility of the host.

Susceptibility is highly variable and dependent upon both the general health of the subject and the specific pathogen in question. Infants, elderly persons, malnourished persons, and persons with concomitant illness are more susceptible than healthy adults.

As an example of the variability in infective doses, studies have shown that 10 or less *Giardia lamblia* and as few as 10 *Shigella dysentariae 1* can cause illness, whereas it may require as many as 1,000 *Vibrio cholerae* or 10,000 *Salmonella typhi* to initiate disease [21]. In one volunteer study, about 25 percent of the subjects who ingested 180 *Shigella Flexneri 2A* were infected and made ill [22]. It has been reported that a maximum of 20 *Entamoeba histolytica* cysts constitutes an infective does [23], and very low numbers of viruses may be able to initiate disease in humans. Toxigenic organisms such as enteropathogenic *Escherichia coli* and *Clostridium perfringens* may require 1×10^{10} organisms per dose [9].

For most organisms, infections occur at lower doses than are required to cause disease. Infection is defined as an immunological response to pathogens by a host without showing clinical signs of disease.

It is impossible to accurately predict the type or concentration of microorganisms in raw wastewater. Table 10-2 illustrates the range of concentration of certain organisms that may be present in municipal wastewater. The general health of the contributing population, the existence of disease carriers in the population, and the ability of infectious agents to survive outside their hosts under a variety of

Table 10-2. Microorganism populations in untreated domestic wastewater [23,29].

Organism	Concentration (No./mL)
Coliform	$0.5\text{-}1 \times 10^6$
Fecal streptococci	$5\text{-}20 \times 10^3$
Shigella	Present
Salmonella	4-12
Pseudomonas aeroginosa	102
Clostridium perfringens	507
Mycobacterium tuberculosis	Present
Protozoan cysts	100
Helminth ova	1
Enteric virus	1-492

environmental conditions all contribute to the occurrence and concentration of pathogens in a particular wastewater.

Since enteroviruses are not normally excreted for prolonged periods by healthy individuals, their occurrence in municipal wastewater fluctuates widely. Viruses shed from an infected individual commonly range from 1,000 to 100,000 infective units per gram of feces [2]. Not every virus that is present in feces is waterborne, however, and many may persist for only a short time in municipal wastewater. It has been calculated that the average enteric virus density in municipal sewage is about 500 units/100 mL [24]; this number may vary considerably. In water-short areas such as Israel, where water use is conservative, concentrations in sewage have been reported to average from 600 to 49,200 plaque-forming units (PFU)/100 mL [25]. Virus densities in sewage are also quite seasonal and are most frequently isolated during the summer and early autumn.

Removal of Microorganisms by Wastewater Treatment Processes

Primary treatment, which is merely a sedimentation process, has only limited effect on the removal of most biological species present in the wastewater. Some of the larger and heavier organisms, such as the eggs of helminths and cysts of protozoa, will settle out during primary treatment, and particulate-associated microorganisms may be removed with settleable matter. Between 50% and 90% of the parasitic eggs and cysts can be removed by primary settling, whereas as little as 25% of the bacteria may be removed during the sedimentation process [26]. Primary treatment does not effectively reduce the level of bacteria or viruses in sewage [27,28].

Conventional biological treatment processes (trickling filters, activated sludge, and oxidation ponds) reduce the quantities of biological organisms found in raw or settled sewage but do not eliminate them. The mechanism of removal is either adsorption or predation. In general, activated sludge processes are more effective in reducing bacteria and virus populations than are trickling filters. Activated sludge typically removes over 90% of the bacteria [29] and 80-90% of the viruses, while trickling filters typically remove 50-90% of the bacteria and the viruses [30,31]. Trickling filters have been shown to remove 30% of the beef tapeworm eggs and over 99% of *Entamoeba histolytic* cysts, whereas activated sludge processes by themselves appear to be ineffective in removing either cysts or eggs [32]. All types of secondary treatment can remove more than 90% of coliform indicator organisms, and, in theory, pathogen removals are in proportion to the reduction of coliforms.

The purpose of most advanced treatment processes is to remove either inorganic or organic constituents. Therefore, the removal of biological contaminants by these processes is only incidental in many cases and, generally, is not too great. An exception is reverse osmosis, which, depending on type of unit and membrane characteristics, degree of wastewater pretreatment, and other factors, can be very effective in removing most viruses and virtually all larger microorganisms. Activated carbon adsorption has been shown to adsorb some viruses from wastewater, but the adsorbed viruses can be displaced by organic compounds and enter the effluent [33,34].

Tertiary treatment consisting of chemical coagulation, sedimentation, and filtration has been shown to remove 99.5% of seeded virus [35]. In addition to effectively removing viruses, this treatment chain reduces the turbidity of the wastewater to very low levels, thereby enhancing the efficiency of the disinfection process that follows filtration. Filtration is also effective in removing the many larger parasites that are resistant to the disinfection levels normally used in wastewater treatment.

The most important treatment process from the standpoint of pathogen destruction is disinfection. In the United States, the most common disinfectant for both water and wastewater is chlorine. The efficiency of disinfection with chlorine is dependent upon the water temperature, pH, time of contact, degree of mixing, presence of interfering substances, concentration and form of the chlorinated species, and nature and concentration of the organisms to be destroyed.

In practice, the amount of chlorine added is determined empirically, based on desired residual and effluent quality, which is usually measured by total or fecal coliform concentration. Unless the wastewater has a very low turbidity, there is a high probability that the disinfected wastewater will not be completely free of bacterial or viral pathogens. In general, bacteria are less resistant to chlorine than are viruses, which in turn are less resistant than parasites.

The destruction of viruses by chlorine is highly variable. Studies [36] indicate that viruses are generally more resistant to chlorine than bacteria. Therefore, the coliform test does not give a reliable indication of the effectiveness of virus destruction by disinfection [37,38].

Ozone is not commonly used for disinfection but has received considerable attention in recent years. However, it is difficult to disinfect secondary effluents with ozone and consistently meet typical bacteriological standards for reclaimed water, because suspended matter reacts with the ozone and thereby leaves less of the ozone available for disinfection [39,40].

It is also possible to reduce the concentrations of bacteria and viruses in wastewater by storing it before use. One study of a test holding pond in Israel found that the concentrations of total coliforms, fecal coliforms, and fecal streptococci in secondary effluent were reduced 2-4 logs during both a 73-day storage time in winter and a 35-day storage time in summer. Enteroviruses were reduced from 1100/100 ml during the winter storage and from 200/100 ml during the summer storage to less than detectable levels during both storage seasons [41].

Survival of Pathogens

Under favorable conditions, enteric pathogens can survive for extremely long periods of time on crops or in water or soil. Factors that affect survival include number and type of organism, soil organic matter content, temperature, humidity, pH, amount of rainfall, amount of sunlight, protection provided by foliage, and competitive microbial flora. For example, a review of the literature [21,42,43] indicates that *Ascaris* ova can survive from 27 to 35 days on vegetables and 730-2010 days in soil, and *Salmonella* spp. can survive from 3 to more than 40 days on vegetables, more than 100 days on grass, and from 15 to more than 280 days in the soil. *Salmonella typhi* have been reported to survive 87-100 days in water, 2-120 days in soil, and

10-53 days on vegetables [42]. In one study, poliovirus and Coxsackie virus inoculated onto vegetables survived for more than four months during commercial and household storage [44] and up to 180 days in saturated soil at 4°C [45]. The range of survival times suggests that pathogens introduced into a field by irrigation with wastewater could survive in the soil or on some crops for extensive lengths of time. A more complete discussion of pathogen survival in soil and transport in percolating water is presented in Chapter 14.

Aerosols

The concentration of pathogens in aerosols is a function of their concentration in the applied wastewater and the aerosolization efficiency of the spray process [46]. Studies have shown that, during the spray irrigation of wastewater, the amount of water that is aerosolized can vary from less than 0.1% to almost 2% with the mean aerosolization efficiency varying from 0.32% to 1.3% [47,48,49,50]. Aerosols are defined as particles ranging from 0.01 to 50 µm in diameter that are suspended in air. Viruses and most pathogenic bacteria are in the respirable size range [51]; hence, a possible direct means of human infection by aerosols is by inhalation. Infection or disease can be contracted indirectly by deposited aerosols on surfaces such as food, vegetation, and clothes. The infective dose of many pathogens is lower for respiratory tract infections than for infections via the gastrointestinal tract; thus, inhalation may be a more likely route for disease transmission than either contact or ingestion [52].

In general, bacteria and viruses in aerosols remain viable and travel farther with increased wind velocity, increased relative humidity, lower temperature, and darkness [47,53,54]. Other important factors include the initial concentration of pathogens in the wastewater and droplet sizes. Studies have shown that relatively high concentrations of bacterial aerosols can be transmitted for considerable distances under optimum conditions. For example, one study found that coliforms were carried 295 to 426 ft (90-130 m) with a wind velocity of 3.4 mph (1.5 m/sec). The authors estimated that fine mist could be carried 984 to 1312 ft (300-400 m) with an 11 mph

(5 m/sec) wind and 3281 ft (1,000 m) or more with stronger winds [43]. Another study found that the mean net bacterial aerosol levels, i.e., the observed minus the simultaneous mean upwind value, were 485 colony-forming units (CFU)/m^3 at a distance of 69-98 ft (21-30 m) from the most downwind row of sprinkler heads in a spray field and 37 CFU/m^3 at 656 ft (200 m) downwind [50]. The sprayed wastewater had received treatment in stabilization lagoons before disinfection with chlorine.

During a recent study in Israel, echovirus 7 was detected in air samples collected 40 m downwind from sprinklers spraying secondary effluent [55]. Aerosol measurements at Pleasanton, California, where undisinfected secondary effluent was sprayed, indicated that the geometric mean aerosol concentration of enteroviruses obtained 50 m downwind of the wetted spray area was 0.014 PFU/m^3 [49]. This concentration is equal to one virus particle in 71 m^3 of air.

Studies [49,56,57] indicate that the use of the traditional indicator organisms to predict human exposure via aerosols results in a significant underestimation of pathogen levels. In those studies, the pathogens survived the wastewater aerosolization process much better than the indicator organisms.

Because there is a paucity of information concerning the health risks associated with wastewater aerosols, health implications regarding this subject are difficult to assess. Most of the epidemiological studies conducted on residents in communities subjected to aerosols from sewage treatment plants--many using subjective health questionnaires--have not detected any correlation between exposure to aerosols and illness. Although some studies have indicated higher incidences of respiratory and gastrointestinal illnesses in areas receiving aerosols from sewage treatment plants than in control areas, the elevated illness rates were either suspected to be the result of other factors, such as economic disparities, or were not verified by antibody tests for human viruses and isolations of pathogenic bacteria, parasites, or viruses [58,59].

The research conducted to date seems to indicate that the health risk associated with aerosols from sewage effluent spray irrigation sites is low, particularly for irrigation with wastewater that has been disinfected. However, sporadic cases may exist where high exposure is experienced, and until more sensitive and definitive studies are conducted to fully evaluate the ability of aerosols to cause disease, prudence dictates that the inhalation of aerosols that may contain viable pathogens should be minimized.

Disease Incidence Related to Wastewater Reuse

There is epidemiological evidence indicating that the reuse of municipal wastewater, particularly for the irrigation of food crops, has resulted in the transmission of disease [43,60]. The majority of documented disease outbreaks have been the result of bacterial or parasitic contamination. In all cases, either raw sewage or undisinfected effluent was the source of irrigation water. These outbreaks demonstrate that sewage is a hazardous material with a significant potential for transmission of infectious disease. However, there have not been any confirmed disease outbreaks in California resulting from the use of reclaimed wastewater.

Although there is little information concerning the occurrence of viral diseases resulting from the reuse of wastewater, the water route of transmission, such as public water supplies, has been implicated in several outbreaks of infectious hepatitis and poliomyelitis. The study of low-level or endemic occurrence of waterborne virus diseases has been virtually ignored for several reasons: (1) present virus detection methods are not sensitive enough to accurately detect low concentrations of viruses in large volumes of water; (2) enteric virus infections are often not apparent, thus making it difficult to establish the endemicity of such infections; (3) the apparently mild nature of most enteric virus infections preclude reporting by the patient or the physician; (4) damage due to enteroviral infections may not become obvious for several months or years [61]; and (5) once introduced into a population, person-to-person contact would become a major mode of transmission of an enteric virus, thereby obscuring the role of water in its transmission.

REGULATORY AUTHORITY IN CALIFORNIA

Wastewater reclamation in California is notable for the large number of reuse operations, the diversity of applications, and the excellent safety record over many years. The principal agencies involved in wastewater reclamation and reuse in California are the following: United States Environmental Protection Agency; Bureau of Reclamation, United States Department of the Interior; California Department of Water Resources; California State Water Resources Control Board; California Department of Health Services; local health agencies; and the nine California Regional Water Quality Control Boards. From a regulatory standpoint, the two federal agencies and the California Department of Water Resources play relatively minor roles in the area of wastewater reclamation.

The U.S. Environmental Protection Agency (EPA) provides the federal share of grants for funding municipal wastewater treatment projects and sets regulations to guide funding of wastewater reclamation projects and to ensure protection of the environment. The EPA also provides technical guidance on health and other issues related to wastewater treatment. The Bureau of Reclamation studies uses of reclaimed water and controls and administers loans under the Small Reclamation Projects Act of 1956. In addition, the Farmers Home Administration has grant and loan programs for small communities. Under appropriate conditions, these federal grants and loans can be used to finance distribution systems to transport reclaimed water from treatment plants to points of use. The California Department of Water Resources (DWR) studies the availability and reuse potential of wastewater, including the environmental effects of reuse. The DWR may also assist in funding research related to wastewater reuse and assists in identifying and planning new projects.

The State Water Resources Control Board (SWRCB) and the Regional Water Quality Control Boards (RWQCB) have the primary responsibility for controlling and protecting the quality of waters in California and for administering water rights. The SWRCB administers the Federal and State Clean Water Grant Program, which is the primary source of financial assistance to local public agencies for the construction of wastewater treatment and disposal facilities. Eligible facilities include treatment plants, conveyance facilities, and, under certain conditions, on-site distribution facilities. In 1977, the Office of Water Recycling was established within the SWRCB to promote wastewater reuse in California and coordinate statewide water reclamation activities.

The California Department of Health Services (DOHS) reviews individual reclamation requirements, project plans, and environmental documents and maintains a wastewater reclamation surveillance program to ensure an adequate degree of health protection. In addition, DOHS has the authority and responsibility under California law to establish health-related standards for wastewater reclamation for many uses, including irrigation. A part of the California Water Code known as the Porter-Cologne Water Quality Control Act [62] contains the enabling legislation for establishment of criteria, as follows:

> "13521. The State Department of Health Services shall establish statewide reclamation criteria for each varying type of reclaimed water where such use involves the protection of public health."

In addition, if it is determined that contamination exists as a result of use of reclaimed water, DOHS and/or local health agencies have the separate authority to order abatement of contamination and issue peremptory orders, as stated in the California Health and Safety Code, Part 3, Division 5, Chapter 6. DOHS also has cross-connection control regulations [63] governing the delivery system requirements with the specific purpose of maintaining strict separation between the reclaimed and domestic water systems. Local health agencies have independent authority and may, if they deem necessary, impose requirements more stringent than those specified by the California Department of Health Services.

The Water Code provides for the nine RWQCBs to establish water-quality standards, to prescribe and enforce waste discharge requirements in order to protect surface and groundwater quality, and, in consultation with DOHS, to prescribe and enforce reclamation requirements. Thus, DOHS's reclamation criteria are enforced by the regional boards, and each wastewater reclamation project must have a permit from the appropriate RWQCB conforming to the DOHS criteria. The relevant sections of the Water Code are as follows:

"13522.5. (a) Any person reclaiming or proposing to reclaim water for any purpose for which reclamation criteria have been established shall file with the regional board of that region a report containing such information as may be required by the board.

13523. Each regional board, after consulting with and receiving the recommendations of the State Department of Health and after any necessary hearing, shall, if it determines such action to be necessary to protect the public health, safety, or welfare, prescribe water reclamation requirements for water which is used or proposed to be used as reclaimed water. Requirements may be placed upon the person reclaiming water, the user, or both. Such requirements shall include, or be in conformance with, the statewide reclamation criteria established pursuant to this article. The regional board may require the submission of a preconstruction report for the purpose of determining compliance with the reclamation criteria.

3524. No person shall reclaim water or use reclaimed water for any purpose for which reclamation criteria have been established until water reclamation requirements have been established pursuant to this article or a regional board determines that no requirements are necessary."

In 1978 additions were made to the Water Code that, if specific conditions are met, require the use of reclaimed, rather than potable, water to irrigate greenbelt areas. The appropriate sections are as follows:

"13550. The Legislature hereby finds and declares that the use of potable domestic water for the irrigation of greenbelt areas, including, but not limited to, cemeteries, golf courses, parks, and highway landscaped areas, is a waste or an unreasonable use of such water within the meaning of Section two of Article X of the California Constitution when reclaimed water which the state board, after notice and a hearing, finds meets the following conditions is available:

(a) The source of reclaimed water is of adequate quality for such use and is available for such use.

(b) Such reclaimed water may be furnished to such greenbelt areas at a reasonable cost for facilities for such delivery. In determining reasonable cost, the state board shall consider all relevant factors, including, but not limited to, the present and projected costs of supplying potable domestic water to affected greenbelt areas and the present and projected costs of supplying reclaimed water to such areas, and shall find that the cost of supplying such reclaimed water is comparable to, or less than, the cost of supplying such potable domestic water.

(c) After concurrence with the State Department of Health Services, the use of reclaimed water from the proposed source will not be detrimental to public health.

(d) Such use of reclaimed water will not adversely affect downstream water rights, will not degrade water quality, and is determined not to be injurious to plant life.

The state board may require a public agency or person subject to this article to furnish such information as may be relevant to making the findings required by this section.

13551. A person or public agency, including a state agency, city, county, city and county, district, or any other political subdivision of the state, shall not use water from any source of quality suitable for potable domestic use for the irrigation of greenbelt areas when suitable reclaimed water is available as provided in Section 13550; provided that any such use of reclaimed water in lieu of the extraction of groundwater shall, to the extent of such reclaimed water so used, be deemed to constitute a reasonable beneficial use of the groundwater and such use of reclaimed water shall not cause any loss or diminution of any existing water right however acquired."

REGULATIONS

California Regulations

There is some risk of human exposure to pathogens in almost every wastewater reclamation operation, but in general the health concern is in proportion to the degree of human contact with the water and the adequacy and reliability of the wastewater treatment processes.

Pursuant to Section 13521 of the Water Code, the DOHS has established statewide reclamation criteria, which were revised most recently in 1978. A basic objective of DOHS's regulations, entitled "Wastewater Reclamation Criteria" [64], is to assure health protection without unnecessarily discouraging wastewater reclamation. The regulations specify wastewater reuse standards for uses involving irrigation, impoundments, and groundwater recharge. The regulations include water-quality standards, treatment process requirements, sampling and analysis requirements, operational requirements, and treatment reliability requirements. The required degree of treatment increases as the likelihood of human exposure to the wastewater increases. The treatment and quality requirements for the irrigation uses covered by the Wastewater Reclamation Criteria are summarized in Table 10-3. The reclamation criteria are intended to assure an adequate degree of health protection from disease transmission and do not specifically address the potential effects of reclaimed water on the crops or soil. The complete set of regulations is contained in Appendix D.

For most uses of reclaimed water, the regulations do not require an extensive monitoring program to demonstrate reclaimed water quality. Such a requirement would eliminate the many small reclamation operations that would not be able to afford the expense of a sizable monitoring effort. Consequently, insofar as possible without jeopardizing the regulatory intent, descriptive terms well understood by professionals in the wastewater treatment field are used rather than quantitative limits of specific parameters. For example, an "adequately oxidized wastewater" is required rather than effluent meeting a specific biochemical oxygen demand (BOD), suspended solids, or other parameter. However, analyses for these specific water quality parameters may be required by the RWQCBs as part of the effluent discharge requirements.

Table 10-3. Wastewater treatment and quality criteria for irrigation [64].

Treatment level	Coliform limits	Type of use
Primary		Surface irrigation of orchards and vineyards
		fodder, fiber, and seed crops
Oxidation and disinfection	$\leq$23/100 mL	Pasture for milking animals
		Landscape impoundments
		Landscape irrigation (golf courses, cemeteries, etc.)
	$\leq$2.2/100 mL	Surface irrigation of food crops (no contact between water and edible portion of crop)
Oxidation, coagulation, clarification, filtration[a], and disinfection	$\leq$2.2/100 mL max. = 23/100 mL	Spray irrigation of food crops
		Landscape irrigation (parks, playgrounds, etc.)

a. The turbidity of filtered effluent cannot exceed an average of 2 turbidity units during any 24-hour period.

Crop Irrigation

Wastewater containing pathogens can contaminate crops directly by contact during irrigation or indirectly as a result of soil contact. Crops can also be contaminated by blowing dust or by workers, birds, and insects that convey organisms from irrigation water or soil to the edible portion of the crop.

Where there is a minimal health risk, based on degree of contact and water quality, the regulations are extremely liberal and require a very low level of treatment. Primary effluent is acceptable for the surface or spray irrigation of fodder, fiber, and seed crops and for the surface irrigation of orchards and vineyards. Primary effluent is defined [64] as "effluent from a wastewater treatement plant process which provides removal of sewage solids so that it contains not more than 0.5 mL/L of settleable solids as determined by an approved laboratory method." Primary sedimentation usually removes less than 50% of coliforms and pathogenic bacteria from sewage, and it is relatively ineffective in removing viruses and protozoa [21,27,28].

Primary effluent has been used for the surface irrigation of orchards and fodder, fiber, and seed crops for more than 60 years without any observed detrimental health effects [65]. With proper application and use area controls, human contact with the wastewater is minimal. Allowing the fields to dry before grazing or harvest of fodder crops substantially reduces the number of viable pathogens on the crop before animal consumption. Although there has not been any apparent increase in beef tapeworm infections in California resulting from the use of primary effluent for pasture irrigation, no detailed studies have been conducted to determine whether such infections are more prevalent in cattle grazing on pasture irrigated with primary effluent than in cattle grazing on pasture irrigated with water of non-sewage origin.

Primary effluent is also acceptable for the surface irrigation of orchards and vineyards because of the distance between the irrigated ground and the edible crops. Pathogens in the wastewater do not readily penetrate into fruits or vegetables unless the skin is broken [21]. In one study where soil was inoculated with poliovirus, viruses were detected in the leaves of plants grown in the soil only when the plant roots were damaged or cut [66]. Although absorption of virus by plant roots and subsequent acropetal translocation has been reported by Murphy and Syverton [67], the authors noted that it probably does not occur with sufficient regularity to be important as a mechanism for transmission or for interepidermic survival of virus. Therefore, the likelihood of translocation of pathogens through the trees or vines to the edible portions of the crops is extremely low, and the health risks are negligible. The regulations prohibit harvesting of fruit that has come in contact with the irrigation water or the ground.

As previously stated, many pathogens can survive for extended periods on plants and in soil; thus, simply providing extensive periods between irrigation and crop harvest, or providing commercial storage before public sale, cannot be relied upon to eliminate all pathogens. Consequently, in the case of food crops, emphasis should be placed on eliminating the pathogens from the wastewater before irrigation, processing the crop to destroy pathogens before public sale, or preventing direct contact between the wastewater and the edible portion of the crop to minimize the risks of disease transmission.

The risks vary depending on the type of crop and method of irrigation. If food crops are surface-irrigated such that there is no contact between the edible portion of the crop and the reclaimed water, a disinfected, secondary-treated effluent is acceptable. The wastewater is considered adequately disinfected if at some location in the treatment process the median number of coliforms does not exceed 2.2/100 mL. The median value is determined from the bacteriological results of the last seven days for which analyses have been completed, and, as in all sections of the regulations specifying coliform limits, daily sampling is required.

As indicated above, the regulations require sampling the effluent for coliforms rather than testing for infectious agents directly. In recognition of the many constraints associated with analyzing wastewater for all of the potential pathogens that may be present, it has been common practice to use a microbial indicator or surrogate to indicate fecal contamination of water. Testing for all pathogens would require use of a vast number of tests, some of which involve complex, time-consuming, expensive, and often insensitive procedures. Further, the concentrations of different pathogens vary in different wastewaters, which may make detection difficult and unreliable. This variability is a function of the number of intestinal infections that occur at different times in the contributing warm-blooded population and is independent of the concentrations of nonpathogenic indicator organisms.

The total coliform group contains bacteria that are always in the intestinal tract of humans and other mammals. Coliforms occur naturally in the feces of warm-blooded animals in higher concentrations than pathogens and are easily and unambiguously detectable, exhibit a positive correlation with fecal contamination, and generally respond similarly to environmental conditions and treatment processes as many pathogens. Consequently, the DOHS has selected the total coliform group of bacteria as the indicator organism to determine the presence or absence of fecal contamination in water and at the same time suggest the presence or absence of infectious agents. Although it is true that the total coliform group includes strains that are not directly associated with fecal matter, the total coliform indicator system is not overly conservative. There have been instances where the total coliform test has not indicated the presence of waterborne *Salmonella* and *Giardia*, and the coliform group is known to be less resistant to chlorine disinfection than some pathogenics, such as protozoan cysts and enteric viruses.

The total coliform limits prescribed in the Wastewater Reclamation Criteria are based on the multiple tube fermentation technique and are reported in terms of the Most Probable Number (MPN). In the multiple tube procedure, replicate tubes of a selected test medium are inoculated with serial dilutions of a water sample. The greater the number of replicates of each sample volume in a dilution series, the greater the test precision. The MPN is actually an estimate based on certain probability formulas. For example, for an MPN index of less than 2.2/100 mL, the 95% confidence limits are between 0 and 6/100 mL, when five 10-mL portions are used in the analysis [68].

Because of the short distances between the irrigating water and the crops in most surface-irrigation systems, there is a likelihood of occasional contact between the wastewater or contaminated soil and crop as a result of splashing, transmission by vectors, windblown dust, or flooding caused by overapplication of the reclaimed water. However, in consideration of the relatively low frequency of such occurrences, it would be unrealistic to require that the irrigation water be free of all infectious agents. Typically, wastewater meeting a total coliform limit of 2.2/100 mL must receive a high level of treatment and, while the effluent not assuredly pathogen-free, it does not impose undue health risks when used for the surface irrigation of food crops.

Spray irrigation of food crops requires much more stringent requirements than surface irrigation because of the direct contact between the wastewater and the crops. Organisms contaminating food crops remain viable on the food surface unless they succumb to desiccation, exposure to sunlight, starvation, or action of other organisms or chemical agents. The reliability and completeness of pathogen inactivation by these mechanisms are questionable. Therefore, tertiary effluent that is pathogen-free is required for the spray irrigation of all crops that are eaten or sold raw. The surface irrigation of root crops, such as carrots, beets, and onions, also results in direct contact between the crop and the wastewater; hence, irrigation of those crops is subject to the same requirements.

The DOHS recognizes that identification and enumeration of viruses in water and wastewater is hampered by the limitations of sampling techniques, problems of concentration of samples, the complexity and high cost of laboratory procedures, and the limited number of facilities having the personnel and equipment necessary to perform the analysis. Furthermore, the laboratory culturing procedure to determine the presence or absence of viruses in a water sample takes about 14 days. Therefore, in lieu of a virus standard, the treatment and quality requirements stated above are specified, in part, to assure that the wastewater will not contain any pathogens, including viruses.

Selection of the treatment chain specified in the Wastewater Reclamation Criteria was predicated on studies conducted several years ago to determine the virus removal capability of advanced waste-treatment processes. More recent studies [35,69] have verified the effectiveness of the treatment chain, which includes oxidation, chemical coagulation, clarification, filtration, and disinfection. Data indicate that wastewater receiving such treatment and meeting specific constituent levels will be essentially free of all measurable pathogens. The quality requirements include the total coliform limit of 2.2/100 mL and turbidity limits. The turbidity standard is tied to the definition of filtered wastewater, which states that the turbidity cannot exceed an average of 2 turbidity units and cannot exceed 5 turbidity units more than 5% of the time during any 24-hour period. The regulations require that turbidity analyses shall be performed by a continuous recording turbidimeter. Experience has shown that these turbidity levels are readily achieved in well-operated wastewater treatment facilities employing chemical coagulation and filtration-unit processes and greatly enhance the effectiveness of the subsequent disinfection process.

Exceptions may be made to the quality requirements for reclaimed water used for the irrigation of food crops that undergo sufficient physical or chemical commercial processing to destroy pathogens before they are sold for human consumption. Exceptions are subject to approval by the DOHS based on a thorough evaluation in each case of the ability and reliability of the processing to destroy pathogens. Because of opportunities for transmission of infectious organisms created by handling crops that may be contaminated, it is not acceptable to sell the crops or otherwise allow the public to handle them before processing. This provision assures that the transmission link is severed and that contaminated raw foods are not brought into food-preparation environments.

There are no specific regulations in California pertaining to the packaging, distribution, or sale of food crops grown with reclaimed municipal wastewater. The DOHS has taken the position that properly designed and operated food crop irrigation projects meeting all appropriate standards do not present undue health risks to the consumer, and the DOHS will not require or recommend special labeling informing the public that the crops were irrigated with reclaimed wastewater.

Landscape Irrigation

The Wastewater Reclamation Criteria differentiate between types of landscape irrigation based on public access to the use area and expected exposure to the wastewater. Section 60313 of the regulations (Appendix D) covers landscape irrigation.

Wastewater that has received secondary treatment and has been disinfected to a level of 23 total coliforms per 100 mL (as required for landscaping) may contain both bacterial and viral pathogens, so direct contact with the water should be avoided. However, assuming that irrigation occurs when the public is excluded from the use area and that there is sufficient time for the grounds to dry out before use, there will not be any direct contact with the wastewater, and the health risks are dependent on indirect contact only--contact with grass, shrubs, objects, etc. that were previously wet with the reclaimed water. Indirect contact of this nature is relatively infrequent at the types of use areas identified in part (a) of Section 60313 (golf courses, freeway landscapes, and cemeteries) and does not warrant requiring the wastewater to be free of all infectious agents.

On the other hand, parks, playgrounds, schoolyards, and similar areas are more intensely used areas, and children may be more susceptible to some of the pathogens typically found in sewage. Therefore, the quality and treatment requirements for this type of landscape irrigation are identical to those required for the spray irrigation of food crops.

The possibility of disease transmission by aerosols or windblown spray from landscape irrigation sites must also be considered, because of the proliferation of reuse projects in urban settings or adjacent to populated areas. The degree of hazard depends on several factors, including degree of wastewater treatment, extent of aerosol or water-droplet travel, proximity to populated areas or areas accessible to the public, prevailing climatic conditions, and design of the irrigation system.

Although the regulations state that secondary treated wastewater meeting a total coliform requirement of 23/100 mL is acceptable for golf course irrigation, the DOHS has taken the position that a higher quality effluent, i.e., that meeting the requirements specified in Section 60313(b) of the Wastewater Reclamation Criteria, is necessary in situations where reclaimed water spray or aerosols are not confined to the use area and reach populated areas. Experience has shown that it is virtually impossible to prevent wastewater sprays or aerosols generated at golf courses from reaching private residential areas that abut fairways and/or greens. Therefore, the DOHS recommends that reclaimed water used to irrigate golf courses where residential property lots abut the fairways or greens be essentially pathogen-free and, hence, comply with Section 60313(b) of the Wastewater Reclamation Criteria.

While the Wastewater Reclamation Criteria require specific treatment unit processes in conjunction with effluent quality requirements, other unit processes may provide equivalent levels of treatment. The regulations are not intended to stifle research, development, and implementation of alternative or innovative treatment schemes, and the reclamation criteria include a section that addresses this issue. Section 60320.5 states that methods of treatment other than those mentioned in the Wastewater Reclamation Criteria may be acceptable if they can be demonstrated to be equivalent to the treatment methods specified in the regulations.

Treatment Reliability

The need for adequate treatment is obvious, but it is not so clearly recognized that there is an equally important need to assure reliability of treatment. Several field investigations of municipal wastewater treatment plants in California have documented that, until recently, wastewater treatment reliability has been a neglected phase of treatment plant design, construction, and operation [70,71,72,73]. The increase in reclamation operations and the more frequent use of reclaimed wastewater in public areas has increased the population that may be exposed to wastewater; consequently, the potential for illness resulting from an improperly treated water being delivered to the use areas has also increased. Thus, it is apparent that provisions are necessary to ensure reliability of treatment if a minimum health risk is to be maintained during the use of reclaimed municipal wastewater.

The Wastewater Reclamation Criteria contain both design and operational requirements necessary to ensure a minimum level of treatment reliability. Reliability features are described in Appendix D. Regardless of the automation built into a plant, mechanical equipment is subject to breakdown, and qualified, well-trained operators are an absolute necessity to assure reliable production of an acceptable water. This is reflected in the regulations, and certified personnel are required at all wastewater reclamation plants.

From a public health standpoint, provisions for adequate and reliable disinfection are the most essential features of the treatment process. Where disinfection is required, the reclamation criteria specify that a number of features must be incorporated into the system to ensure uninterrupted chlorine feed.

Most wastewater treatment facilities use fewer instruments and automatic control devices than closely related water-supply and chemical-processing plants. One nationwide study of 50 wastewater-treatment facilities found that the average secondary treatment plant allocates about 3% of construction costs for installed instruments, whereas water-supply and chemical-processing plants allocate about 6% and 8%, respectively [74]. If treatment-process efficiency and reliability are to improve, suitable measuring devices must be available to permit real time control. For example, automatic control loop systems that continuously monitor effluent chlorine residual and adjust the chlorine dosage to maintain a pre-determined residual are becoming increasingly prevalent at wastewater-reclamation facilities. Continuous recording turbidimeters, which automatically divert wastewater to intermediate storage ponds when the turbidity exceeds prescribed limits, have also proven to be effective control devices. Undoubtedly, as the need for adequate reliability becomes more widely recognized by regulatory and other control agencies, more sophisticated sensors, controllers, and recorders will be developed and utilized as integral components of wastewater-treatment systems.

In 1974, the EPA published a technical bulletin entitled "Design Criteria for Mechanical, Electric, and Fluid System and Component Reliability" [75] as a supplement to the 1970 Federal Guidelines for Design, Operation and Maintenance of Wastewater Treatment Facilities [76]. This bulletin spells out minimum design requirements and gives guidance on design for high reliability.

EPA's Municipal Environmental Research Laboratory recently published a handbook entitled "Identification and Correction of Typical Design Deficiencies at Municipal Wastewater Treatment Facilities" [77]. The handbook describes deficiencies that contribute to performance and reliability problems, poor safety practices, and/or decreased flexibility of plant process control. It is intended to provided guidance that will make designs more operable and maintainable at less cost, as well as more flexible in providing adequate performance during times of changing influent characteristics.

A national study of 103 biological wastewater treatment plants found that the ten major causes of poor plant performance were attributable to inadequate or incorrect sampling and testing procedures for process control, improper technical guidance, ineffective operation and maintenance manual instruction, and significant design deficiencies [78]. One of the study recommendations was that federal and state regulatory efforts be directed toward enforcement and accountability to encourage optimum performance from existing facilities. A similar study of 50 treatment plants found that only 13 of the 50 facilities consistently met minimum secondary treatment standards and that of the top ten, factors limiting performance were process-design-oriented [79].

An investigation of mechanical, electrical, and fluid system failures in 21 secondary treatment plants determined that 91% of the failures could have been prevented or mitigated if the reliability design criteria had been met [80]. Inclusion of reliability features, although lessening the probability that inadequately treated effluent will be discharged from the treatment plant, do not provide for failsafe reliability.

Other States and Countries

Several countries have developed standards governing the quality of wastewater used for irrigation purposes; in many cases, the standards are quite different from California's regulations. For example, in Germany, biological treatment and chlorination are required for the irrigation of pasture [81]. Irrigation of crops for human consumption that will be processed to kill pathogens must cease at least four weeks before harvesting. Potatoes and cereals are the only nonprocessed crops for which reclaimed water may be used for irrigation, and irrigation is allowed only through the flowering stage.

In South Africa, heavily chlorinated tertiary effluent is required for the irrigation of orchards, vineyards and fodder crops, and disinfected wastewater containing less than 1000 coliform organisms per 100 mL in 80% of the samples is used for processed food crops. The only nonprocessed food crops that can be irrigated with reclaimed water are fruits that are peeled before eating.

Wastewater reclamation activities in this country have generally been limited to water-short areas, particularly in the west and southwest. A few states other than California have independently developed, or are in the process of developing, reuse standards or guidelines, and as could be expected, they vary substantially. Brief summaries of existing or proposed guidelines and regulations from three states are given below to illustrate this variability.

The State of Texas does not have comprehensive wastewater reclamation regulations but does have guidelines for some irrigation uses. Undisinfected secondary effluent is allowed for pasture irrigation, and only food crops that will be processed are allowed to be irrigated with reclaimed water. Golf course irrigation requires a disinfected secondary effluent having a maximum BOD of 20 mg/L, a maximum suspended solids level of 20 mg/L, and a fecal coliform limit of 200/100 mL. Irrigation is not allowed at landscape areas that have uncontrolled access, such as parks and playgrounds.

Proposed regulations in Florida require that reclaimed water used to irrigate fodder crops, sod farms, or similar areas where public access is restricted must be secondary effluent. That effluent must be disinfected to produce a combined chlorine residual of 0.5 mg/L after 15 min of contact at maximum daily flow or after 30 min contact time at average daily flow, whichever provides for the higher level of public health protection. This basic disinfection level cannot result in more than 200 fecal coliform organisms per 100 mL of effluent sample. For the irrigation of golf courses, cemeteries, parks, and other landscaped areas accessible to the public, it is proposed to require advanced waste treatment and disinfection such that fecal coliforms in the effluent are below detectable limits and maximum BOD and total suspended solids are below 20 mg/L and 5 mg/L, respectively. Maintenance of 1 mg/L total chlorine residual for 15 min contact time at maximum daily flow or after 30 min contact time at average daily flow would also be required.

The State of Arizona has proposed regulations that do not require specific treatment processes but do prescribe effluent quality limits for various types of irrigation uses. From a practical standpoint, secondary treatment is the minimum necessary for any type of irrigation use, including fodder, fiber, or seed crop irrigation. Playground irrigation requires that the fecal coliform level in the effluent not exceed a geometric mean of 25 colony-forming units (CFU) per 100 mL with a maximum allowable level of 75 CFU per 100 mL in any sample, in addition to a turbidity limit of five turbidity units and an enteric virus limit of 125 PFU per 40 L. The proposed regulations for unprocessed food crop irrigation are even more stringent. They specify that the fecal coliform level in the effluent cannot exceed a geometric mean of 2.2 CFU/100 mL or 25 CFU/100 mL in any sample. Also, the maximum allowable turbidity is one turbidity unit, and it is specified that the final effluent cannot contain more than one virus PFU per 40 L.

Use Area Controls

The management of the reclaimed water once it leaves the treatment facility is an important facet of the overall reclamation operation. In order to minimize health risks and aesthetic or other problems, tight controls should be imposed on the delivery and use of the water. Failure to adhere to use restrictions can lead to health and public acceptance problems fully as serious as those associated with failure in the treatment system.

It was previously stated that in California, the regulations for any specific use are based on the expected degree of contact with the reclaimed water. The anticipated degree of contact, in turn, is based on compliance with proper design and operational controls at the use area. In recognition of the need to minimize health risks during delivery and at the point of reuse, the California Department of Health Services has developed use area guidelines that describe appropriate safety precautions and operational procedures, such as cross-connection control provisions, color-coded reclaimed water lines and appurtenances, key-operated valves and outlets, fencing, signs, control of aerosols and windblown spray, and provisions for worker protection.

Water reclamation requirements adopted by the RWQCBs normally include specific use restrictions appropriate for that individual project. Experience indicates that the key to assuring compliance with use area restrictions is careful project design, especially when extraordinary diligence would be required of the user in the absence of such design.

Cross-Connection Control

The reclaimed water transportation and distribution pipelines and appurtenances must be kept completely separate from the potable water systems. At service connections, the public water supply should be protected by an air-gap separation, a reduced-pressure-principle backflow-prevention device, or other protective devices acceptable to the regulatory agency. Although studies [82,71] have shown that cross-connections are not frequently found at use areas, cross-connection control regulations should be strictly enforced to assure that unnecessary risks are avoided.

Reclaimed water piping might easily be mistaken for that of domestic water if it is not properly identified. There are various ways to diminish the possibility of cross-connections at the use area. The reclaimed water lines and appurtenances can be color-coded or similarly marked for easy identification by workers. It may be possible to use different piping material for reclaimed and potable water lines. Complete records should be kept showing the plans and specifications of all types of water lines at the use area, and no water lines should be tapped into without first consulting these plans to ensure against cross-connections.

All valves and outlets from the reclaimed water system should be tagged with an appropriate warning, in addition to being color-coded, banded, or similarly marked for identification. Where hose bibbs are present on domestic and reclaimed water lines, it is advisable to establish differential sizes to preclude interchange of hoses.

Maximum attainable separation of reclaimed water lines and domestic water lines should be practiced in order to minimize construction accidents resulting in pipeline breaks, infiltration of wastewater from leaking reclaimed water lines into domestic water lines, or accidental cross-connection between reclaimed water and domestic water systems. The appropriate regulatory agency should be consulted regarding the type of piping materials that may be used for the reclaimed water lines.

Prevention of Public Contact

Adequate means of notification should be provided to inform the public that reclaimed water is being used. Such notification should include the posting of conspicuous warning signs. Warning signs should clearly state that the water is reclaimed from sewage and, unless the water is pathogen-free, warn the public to avoid contact with the water. Signs should not merely state "Keep Out" or "No Swimming" but should state "Water Reclaimed from Sewage--Avoid Contact," "Reclaimed Wastewater--Do Not Drink," or other similarly clear, simple, and concise wording. These signs should be located in areas where the public will most likely see them, and the printing should be of a significant size that the signs can be read at a distance. The public should be effectively excluded from contact with low-quality reclaimed water used for irrigation by posting warning signs, or where necessary, by erecting fences.

A study [57] of 19 golf courses in California that use reclaimed water for irrigation showed that only three of the courses had an adequate number of warning signs, and only one course printed a warning notice on the score cards. Of 72 use areas of all types surveyed in that study, less than one-fourth provided adequate public warning signs.

All valves, outlets, and/or sprinkler heads should also be appropriately tagged to warn the public that the water is not safe for drinking or bathing and should be of a type that can only be operated by authorized personnel. To prevent indiscriminate use of reclaimed water, most use areas employ key-operated valves and outlets or quick-coupling devices.

Precautions should be taken to ensure that reclaimed water will not be sprayed on people, walkways, dwellings, passing vehicles, picnic tables, fresh-water sources, reservoirs, or areas not under control of the user. Drinking-water fountains at spray-irrigation sites should also be protected from direct or windblown spray. At any use area frequented by the public, there should be an adequate number of drinking fountains to obviate the need for drinking from the reclaimed water system. At areas such as parks and golf courses, pressure-operated pop-up sprinkler heads are commonly used that have covers flush with the ground surfaces when not in use. This type of sprinkler is effective in preventing people from attempting to wash or drink from the sprinkler heads. All landscape irrigation should be scheduled so that there is ample opportunity for drying before use.

The possibility of disease transmission by aerosols or windblown spray from spray irrigation sites must also be considered where the source of the water is sewage effluent that is not completely disinfected to eliminate pathogens. Design features that would reduce the public health risks associated with spray irrigation are: (1) effective disinfection of the wastewater before spray irrigation to reduce the potential for disease transmission, even if some drift did reach areas frequented by the public; (2) windbreaks or buffer zones around the irrigation areas; (3) low-pressure spray nozzles with large orifices to produce large water droplets and reduce the formation of fine mist, which would be more susceptible to dispersal by the wind; (4) low-profile sprinklers; and (5) surface methods of irrigation. If the proposed spray application site is relatively flat, it may be feasible to use either border or ridge and furrow types of irrigation. The potential for aerosol or fine mist formation would thus be eliminated, as it would be if drip irrigation were utilized.

Some operational features to lessen public health hazards are: spray only during periods of low wind velocity; do not spray when wind is blowing towards sensitive areas subject to aerosol drift or windblown spray; and irrigate at off-hours when the public would not be at areas subject to windblown spray. This could be done during the late night or early morning hours, so that there would be adequate time for the land, soil, and vegetation, to dry before public use.

Confinement of Discharge

The discharge of reclaimed water should be confined to the area designated and approved for discharge. Irrigation should be controlled to minimize ponding, and runoff should be confined and properly disposed.

There should be no runoff from irrigated areas unless it is conducted to approved disposal areas. Surface drainage from fields irrigated with undisinfected effluent contains pathogenic bacteria and viruses, which may seriously contaminate the receiving waters. Although the reclaimed water is considered safe under the controlled conditions maintained in the use area, its safety would become questionable if used outside that area. For example, children may drink runoff collecting in stream beds or bathe in holes containing effluent from the use area.

Ponding and runoff can be minimized through proper operational procedures, such as reducing the application rates and proper placement of sprinkers so that the water is not sprayed on impervious surfaces such as sidewalks and roadways. Adequate containment and disposal of runoff is also important from a legal point of view and will prevent unnecessary and costly lawsuits.

Operational Procedures

Proper planning, operation, and maintenance of water-reclamation use areas is advantageous from economic, aesthetic, and health standpoints. In many cases, especially at privately owned use areas receiving water from public entities, the wastewater supplier may guarantee a specific quantity and quality of reclaimed water. However, a contract may specify that the user must accept all or a set amount of the reclaimed water from a reclamation plant. The user may not be able to reuse all the water and would therefore have to find alternative disposal methods. Therefore, the use area water requirements should be accurately determined before contracting for reclaimed water, and contract provisions should be thoroughly studied before implementation of a reuse scheme.

Wastewater reclamation plants are not fail-safe, and there may be times when reclaimed water will not be delivered to the use area because of problems originating at the reclamation plants. For areas where a constant supply of water is required, the user should be prepared for such occurrences by having an alternative supply of water.

All equipment pertaining to the transport and use of the reclaimed water should be inspected routinely. Preventive maintenance will reduce undue losses of water from leaking pipes and faulty equipment in addition to minimizing the related health hazards.

Use area surveillance and monitoring is a neglected aspect of many reclamation operations. Responsible agencies must take a lead role in assuring that wastewater reclamation projects are designed and operated to fully protect public health. It is entirely appropriate to impose regulatory controls on the conveyance facilities and use area operational practices. Indeed, it would be irresponsible to assume that water-quality requirements are sufficient by themselves to ensure adequate public health protection.

Worker Protection

Adequate measures should be taken for the protection of employees at the various types of use area facilities. It is very important for employees who may come in contact with the reclaimed water to be aware of the potential health hazards involved and not become complacent regarding safety procedures. Before employees are allowed to work in the vicinity of reclaimed water, they should be instructed about the potential for disease transmission from reclaimed wastewater and the precautions they should take. This implies that the personnel in responsible charge of the use areas should themselves be knowledgeable in the health aspects of water reclamation. Everyone involved in the management or operation of a reuse project should maintain a high level of cautiousness, because there is always a potential for equipment failure and human error.

First-aid kits should be available at the use areas, so that all cuts and abrasions can be treated promptly to prevent infection. Although skin contact with the reclaimed water can result in dermatitis and other skin rashes, open wounds are especially susceptible to infection by pathogens, as they present a ready mode of entry into the body. All employees who occasionally come in contact with reclaimed water should change from their work clothing and thoroughly wash before leaving the use area.

At crop-irrigation sites, precautions should be taken to avoid contamination of food taken to irrigated areas, and food should not be taken to areas still wet with reclaimed water. Provisions should also be made for a supply of safe drinking water for field workers. Such water should be carried in contamination-proof containers and protected from contact with reclaimed water or dust. Food and drinking-water containers should not be placed directly on the ground.

PUBLIC ATTITUDES

Historically, decisions to reuse wastewater for beneficial purposes--mostly uses involving minimal public contact--have been based on two principal factors, as discussed in Chapter 1: economics and the need for additional water. Many projects in recent years have involved uses where direct or indirect contact with reclaimed water is likely, and it is becoming clear that public involvement is to be reckoned with in the decision-making process. In recent years, the public sector has become increasingly aware of water pollution and environmental concerns, and public opinions should be carefully considered in any wastewater-reuse program.

Most public-attitude surveys have been directed at reaction toward direct domestic reuse of reclaimed water. Results of five major studies [83,84,85,86] using probability sampling procedures to assess public attitudes toward the use of reclaimed water for drinking are remarkably consistent: somewhat over 50% of each sample selected was opposed to the use of reclaimed water for the highest contact uses. On the other hand, a sizable portion of each sample, on the order of 40%, did not oppose, was positive toward, or would positively accept use of reclaimed water for drinking. A study [87] of 221 respondents of five U.S. cities using a non-probability sampling procedure registered the highest rate of public acceptance, where 77% of the respondents expressed a willingness to drink reclaimed water.

Three of the studies [83,84,87] found a positive relationship between need and attitude toward drinking reclaimed water. Respondents who believed that there was a need for water supply augmentation were more favorable toward the use of reclaimed water for drinking. A positive relationship was also found in three studies [83,86,87] between belief in the adequacy of efficiency of technology and attitude toward drinking reclaimed water. Respondents who believed pollution was serious and widespread were also more favorable toward drinking reclaimed water.

A 1972 study [83] of 972 respondents in 10 communities in California obtained information pertaining to both low- and high-order types of reuse. The strongest opposition--approximately 56%--was directed at the use of reclaimed water for drinking and food preparation. The lowest level of opposition--approximately 1%-- was directed at irrigation of freeway greenbelts and road construction. Thus, it is apparent that the extent of opposition is correlated with the likelihood or extent of close personal contact. Psychological repugnance and concern over purity were most frequently mentioned as reasons for stated opposition. The results of that study did not indicate that cost of treatment was an important determinant of opposition to the use of reclaimed water.

During the recent drought in California, a mail survey was conducted in Irvine, California, a community that uses reclaimed water for a multitude of purposes. Reclaimed water is used for golf course, park, schoolyard, orchard, food crop, and common-area irrigation; common areas include lawns and shrubbery in residential areas that are not under control of the residents. Public awareness of the use of reclaimed water was surprisingly low, for although 58% of the 153 respondents were aware that reclaimed water was used in the city, approximately 75% of the respondents could not identify the source of the irrigation water at the golf course and park [88]. The study further indicated that during drought conditions, respondents were neither willing to pay more for water nor had an interest in water conservation. However, they were willing to accept expanded reclaimed water usages as a means of water augmentation. As in earlier studies, the data indicated that the response of participants was increasingly negative as the proposed uses of reclaimed water were associated more closely with personal contact. Variables that correlated with rejection of reclaimed water were aversion to uncleanliness, aversion to human waste, and over-concern with health.

A 1979 study [89] of 140 Irvine residents indicated that more than 90% of the respondents had favorable attitudes towards using reclaimed water for the irrigation of golf courses, parks, schoolyards, and common areas around residential buildings. Approximately 75% of the respondents had favorable responses toward food crop irrigation, whereas only 28% were in favor of direct potable reuse, a use not occurring (or proposed) at Irvine. During the interviews, the respondents were told that the reclaimed water met all of the DOHS's standards for the existing uses at Irvine. The study included respondents' recommendations regarding future uses for reclaimed water at Irvine. Approximately 56% of the respondents recommended continuation of the existing uses of the reclaimed water, and 5% recommended expansion of the existing uses. Only 5% recommended eliminating existing uses, and almost 25% recommended adding new uses.

Most previous research on public attitudes toward wastewater reclamation dealt with hypothetical uses of reclaimed water that may occur at some unspecified time in the future. A study [90] was undertaken in 1978-79 to assess attitudes toward several wastewater reuse or disposal options actually under consideration for selected communities. This research was necessary to obtain more reliable public responses rather than impersonal projections or speculations. Evaluations of uses ranging from minimal treatment with ocean disposal to tertiary treatment for potable reuse were assessed by the people immediately affected by the options under consideration. Data for this study were obtained by interviewing 140 respondents selected by probability sampling procedures from each of ten California cities. Respondents were presented a detailed analysis of three wastewater treatment and reuse options for their community that covered in a balanced and factual manner the environmental, health, and economic effects of each option. Younger, more affluent, more highly educated respondents who had personally considered the use of reclaimed water had more favorable attitudes than older, less affluent, less-educated respondents who had personally not considered the use of reclaimed water. Further, respondents who believed there was a water supply shortage, that modern technology was capable of treating wastewater, that public health officials would approve certain uses of reclaimed water, and that using reclaimed water would benefit the economy were more favorable in their attitudes.

The results showed that, in general, respondents favored options that protected public health, enhanced the environment, and conserved scarce water resources. For the options assessed in the study, cost did not seem to be an important factor. Options that called for minimal waste treatment and subsequent discharge into the environment without further beneficial reuse were not favored because of environmental and conservation considerations. Options that called for very high degrees of treatment and then use for ingestive purposes were not favored because of the public health considerations. Options that called for high degrees of treatment and then reuse for some beneficial purpose such as agricultural and parkland irrigation were most favored, because they met all three considerations noted.

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CHAPTER 11

LEGAL ASPECTS OF IRRIGATION WITH RECLAIMED WASTEWATER IN CALIFORNIA

Carolyn S. Richardson

INTRODUCTION

As reclaimed wastewater becomes a more significant part of the state water conservation program, legal disputes are likely to arise. The disputes presently foreseeable will come from conflicts over ownership of the reclaimed wastewater and over ambiguities in contractual obligations. Reclamation is a new use of a resource already heavily drawn upon. As water formerly returned to streams after use and treatment is withheld for resale at the treatment site, diminished flow downstream may deprive dependent users of their accustomed supply. Legal action has been taken to block one proposed sale of treated wastewater for this reason [1].

Many existing contracts in California between wastewater reclamation facilities and purchasers do not sufficiently clarify the mutual obligations of the parties. As wastewater reclamation projects have expanded, conflicts have arisen concerning the water entitlements of earlier versus subsequent water users. Although these incidents have been minor, they demonstrate that the best insurance against breach of contract disputes is to clarify the expectations of the parties at the outset. Perhaps more important, the contracts reviewed for this chapter made little provision against liability for personal injury and property damage. Although these hazards may be remote possibilities, they should be addressed in contracts for the sale of reclaimed wastewater; instances of lax compliance with the California Department of Health Services Guidelines have been reported in the past [2].

This chapter focuses on two legal aspects of wastewater reclamation and reuse. The first section discusses the issues of water rights in the ownership and resale of reclaimed wastewater. The second section discusses potential liability and contractual provisions through which exposure to liability may be minimized. As in any area of the law, answers cannot be given with certainty. Until specific legal problems have been addressed by the courts through litigation, or in the legislature through statutes, their solutions can only be stated in probable terms.

STATUTORY PROVISIONS GOVERNING WASTEWATER RECLAMATION

Water Rights in Reclaimed Wastewater

Water rights disputes in the sale of treated wastewater may arise from two sources. The suppliers of raw wastewater may assert an interest in the resale value of the reclaimed wastewater after treatment. Where treated wastewater has customarily been discharged into a stream, downstream water users may assert a right to its continued discharge. As discussed below, recent amendments to the California Water Code have helped resolve the first type of dispute, but the second remains as a potential source of difficulty.

Wastewater treatment facilities have historically operated as wastewater conduits, receiving wastewater from suppliers and discharging it after purification for reuse by others. By reclaiming treated wastewater for direct use in irrigation, a treatment facility abandons this passive role and interrupts the previous reuse cycle. Until recently, the legal means by which a wastewater treatment facility could establish a right to divert wastewater for irrigation were unclear.

Recent changes in the California Water Code, in response to recommendations made by the Governor's Commission to review California Water Rights Law [3], have attempted to resolve these issues of rights to reclaimed water. Unless otherwise provided by agreement, the wastewater treatment facility now has exclusive rights to the treated wastewater as against any supplier of raw wastewater, including suppliers who obtained their water under a water service contract [4]. This concentrates the water rights in the treatment facility, eliminating the need to negotiate with any entity that has contributed to the wastewater. These code amendments make it apparent, however, that the Legislature intended to protect the interests of other legal users who may have established rights to use treated wastewater previously returned to the water system by the treatment facility [5]. The wastewater treatment facility must secure the approval of the

California State Water Resources Control Board (SWRCB) before making any change in the point of discharge or in place or purpose of wastewater use; the Board must review the proposed change to determine that no other legal user will be injured by the withdrawal of water before it may approve the change [6].

Potential injury to downstream users is no obstacle to reclamation in the case of coastal facilities formerly discharging effluent into the sea, or to facilities whose prior land application precluded others from reusing the treated water. In some cases, however, claims of downstream users may raise obstacles to inland facilities previously discharging treated wastewater into streams. A brief review of the system of legal priorities applied to settle conflicts among different water users is helpful to understanding the type of disputes that may arise.

An Overview of California Water Law

California water law is a complex hybrid of different systems. Surface waters are allocated according to rules developed in an uneasy coexistence of riparian and appropriative rights. Groundwater allocation is governed by a system of rights analogous to but distinct from those governing surface waters. In addition, the federal and state water projects create contractual entitlements overlapping the established surface and groundwater rights systems. For our purposes, a brief outline of the two types of surface water rights will suffice to explain water right priorities.

Riparian rights. The riparian water right attaches to land adjacent to a watercourse. The owner of such land may claim a right to use as much of the natural flow of the watercourse as is reasonably necessary to use the land for certain established purposes, among which are household needs, watering domestic stock, and irrigating the riparian property. The significance of this right in the priorities scheme is twofold: it is generally superior to appropriative rights, and it is not extinguished by non-use but can remain dormant endlessly to be asserted when the riparian property is developed. In times of shortage, those holding riparian rights must share the available water among themselves but may defeat the rights of water appropriators entirely [7].

Appropriative Rights. The appropriative water right allows the diversion of water for use on land not bordering a watercourse. This right is not bound to a particular purpose, but it is fixed in amount by the amount claimed at the time of diversion. The water user may change his use or transfer his right so long as the point of diversion and the point of return to the stream are not changed in a manner that interferes with the uses of others. If the amount of water consumed in beneficial use diminishes for five years or more, the right is diminished in quantity and may not be reasserted in its prior amount. Among appropriators, in times of shortage there is no apportioning the loss; a senior appropriator may force a junior appropriator to relinquish his supply [8].

In California, both types of water rights may exist on one stream. There is a long history of litigation determining priorities between riparians and appropriators [9]. The California Constitution was amended in 1928 to impose a prohibition against water waste under either type of right. If a riparian's use is found to be a waste of water, it will not be upheld against the reasonable and beneficial use of an appropriator [10]. However, such a finding is uncommon. The general rule remains that the riparian user making reasonable beneficial use of the water has a right superior to that of the most senior appropriator.

The Permit System. A large obstacle to developing new uses of water is the uncertainty regarding the nature and extent of water rights already existing in a watercourse. California established a permit system in 1914. Before 1914, an appropriation could be made simply by diverting water and putting it to beneficial use; after this date, an appropriation required a permit [11]. The permit procedure is part of the jurisdiction of the SWRCB, which issues permits subject to terms designed to protect existing water rights. The benefit of the permit system is that it brings some degree of certainty and reliability to water supplies, thereby encouraging commercial investment.

An appropriative water right permit has a priority fixed by the date the application is filed, and the amount is recorded [12].

If all rights were within the permit system, greater certainty could be achieved, but not all rights are within the system. The 1914 statute specifically exempted riparian and pre-1914 appropriative rights. Changes or transfers of such rights may be made without notifying the SWRCB [13]. The owner of a post-1914 permit must petition the SWRCB for approval of a change in the point of diversion or in the place or nature of use [14], and the SWRCB may not approve the change if it determines that another legal user will be injured [15]. Although the holder of a pre-1914 right is subject to the common-law prohibition against a change in use that would injure other users, the practice of unrecorded changes very likely has led to an undetected increase in the quantity claimed under these rights over time, while preserving the pre-1914 priority date.

In addition to the unrecorded riparian and appropriative rights, there are at least two other sources of uncertainty: municipal entitlements [16] and state filings [17]. Municipal entitlements enable a municipality to claim a right senior to that of any other user for all amounts necessary to fill its municipal uses [18]. This right expands with the size of the municipality. State filings allow the Department of Water Resources to file claims for unappropriated water needed in a general plan of development. These claims are given a priority date set by the date of filing, but the water is left in the stream until required for development. This creates an apparent availability of water that may later be withdrawn if a permit is granted on a state filing.

Often it cannot be determined with certainty whether there is surplus water in a stream available for appropriation. On the basis of prior studies and hearings on protested applications, the SWRCB believes it can estimate the amount available with some reliability [19]. Since all permits are issued subject to prior rights, any shortages that occur should be borne by the most junior appropriator.

Rights to Reclaimed Wastewater

As noted previously, a recent amendment to the Water Code provides that the owner of a wastewater treatment facility shall hold the exclusive right to the treated wastewater as against any supplier of water entering the facility, unless there has been an agreement to the contrary. This amendment should reduce the likelihood of disputes that might otherwise arise between wastewater treatment facilities and upstream water users as wastewater reclamation begins to be recognized as a means of producing a valuable commodity.

Unfortunately, the Water Code does not address the possibility of disputes arising between owners of wastewater treatment facilities and downstream water users who may have been relying under their appropriative or riparian rights upon treated wastewater previously released by the treatment facilities. These downstream users may challenge the legal authority of a treatment facility to redirect its return flow when the owner of the facility petitions the SWRCB for approval of the reclamation project, or they may later challenge the priority of the treatment facility's water right when the demand for water exceeds the supply. The SWRCB cannot approve a proposed reclamation use if it finds that any legal user will be injured (text, page 11-3, note 6). Despite having obtained approval at the outset, however, the treatment facility may lose its water to future challengers unless it has demonstrable evidence that it has a right to divert the amount of water it reclaims, and that this water right predates the rights of the challengers. Ordinarily, such evidence is provided by a permit to appropriate water.

The new provisions in the Water Code do not require the owner of a treatment facility to obtain an appropriative water right before diverting return flow for reclamation: instead, the owner is allowed to petition the SWRCB for approval of a "change in point of discharge, place of use or purpose of use of treated wastewater." The code states that the Board shall review the proposed changes pursuant to the provisions applicable to changes in point of diversion, place of use, or purpose of use under an appropriative permit [20], a procedure that can be simpler than that required to obtain a new appropriative right.

The legal effect of obtaining Board approval for a new use of reclaimed wastewater under this change petition procedure is unclear. The fact that the Legislature provided this procedure and did not direct the owner of the treatment facility to apply for an appropriation permit may indicate that it intended to encourage reclamation by establishing a new means of obtaining a right to divert and use water. The hazard for the wastewater treatment facility relying on this new statutory procedure is that in simply directing the SWRCB to review reclamation change petitions under a procedure originally designed for changes under existing appropriation permits, the Legislature did not provide a means for establishing a priority date or quantity for the new reclamation use. Moreover, the Legislature did not state that water approved for reclamation under this procedure would no longer be available for appropriation by others. These uncertainties may leave the wastewater treatment facility open to future challenges, even though it has obtained Board approval to reclaim water under a petition for change.

In most cases, the procedural burden of obtaining approval of a change petition will not differ significantly from that of obtaining an appropriation permit. Under both procedures, the applicant must give notice: usually actual notice to known water users, and publication in the affected locale. Under both procedures, the Board must examine the effect of the proposed reclamation use on other lawful users of water and conduct a public hearing on any unresolved protests. Depending upon the magnitude of the proposed reclamation project and the complexity of local water rights issues, the wastewater treatment facility owner may find that the change petition procedure offers no significant short-cut to approval [21].

In view of these procedural similarities and in view of the greater certainty represented by a permit to appropriate water, in most instances it will be advisable for the owner of a wastewater treatment facility to file an application and obtain an appropriation permit before diverting treated wastewater for reclamation. It is particularly important to consider an application for an appropriation permit if substantial investments will be made, or if the proposed reclamation will divert water that historically has been returned to the stream for reuse by others. An application form is found at Appendix C.

Parallel Service Statutes

The treatment facility desiring to sell its reclaimed wastewater may be liable to pay compensation to established suppliers of fresh water under the "parallel service statutes" [22]. These statutes were originally enacted in 1915 to protect the investment of private utilities from later competition by public entities but have since been expanded to protect established public entity suppliers from encroachment by private utilities [23]. Under the parallel service statutes, an established fresh-water supplier is entitled to demand compensation to the extent that it is damaged by any of its water service facilities being made inoperative, reduced in value, or rendered useless to it as the result of a competing water supplier entering its service area [24].

The sale of treated wastewater may be considered a competing service under these statutes. The Health and Safety Code prohibits sewage districts from supplying treated wastewater within the water service area of a city, water district, or other local agency without its consent [25]. Fresh-water suppliers are interpreting this provision as enabling them to demand compensation for any facilities already serving the sites where reclaimed wastewater is to be applied [26].

The effect of the parallel service statutes may be to discourage the sale of reclaimed wastewater by parties who are not established suppliers of fresh water. Most localities where treated wastewater could be sold for landscape irrigation are within the service area of a fresh-water supplier [27]. Applying these protective statutes to require compensation from reclaimed water providers under these circumstances, however, conflicts with the state policy promoting the use of reclaimed water for greenbelt irrigation [28]. Furthermore, restrictions on the use of such water should prevent its sale from appreciably undercutting the rate base of an established fresh-water supplier. For these reasons, the applicability of the parallel service statutes to the sale of reclaimed wastewater for landscape irrigation is questionable, and if compensation to fresh-water suppliers is required, the amount may be minimal.

Nonetheless, it is advisable to consult at the outset with all fresh-water suppliers serving the target application area to determine whether there may be any parallel service difficulties. One example of an accommodation between a reclaimed water purveyor and a supplier of fresh water is the arrangement between the Walnut Valley Water District (WVWD) and the Rowland Area County Water District (Rowland). A copy of a Memorandum of Understanding between WVWD and Rowland is found at Appendix D. When WVWD transports reclaimed wastewater into the service area of Rowland, the districts negotiate a paper sale of the water. Rowland then bills customers within its service area and remits the wholesale price to WVWD. The reclaimed water remains in WVWD pipes until it reaches the ultimate user. Under this arrangement, the supplier of the reclaimed water retains physical control over the water, while the local fresh-water supplier retains control over pricing in its district [29].

The effect of parallel service statutes on wastewater reclamation projects will vary considerably with the circumstances of each case. Wherever the proposed use of reclaimed water will be within the service area of an established fresh-water supplier, the reclaimed-water purveyor should give early consideration as to how potential disputes can be resolved.

THE WASTEWATER SUPPLY CONTRACT: PROVIDING AGAINST LIABILITY FOR PERSONAL INJURY AND PROPERTY DAMAGE

The purpose of including a discussion of limiting exposure to liability by contract is not to equip the reader to draft contracts, but merely to acquaint the reader with the complexity of this field. As noted previously, a number of wastewater supply contracts reviewed by this author made little attempt to allocate liability for personal injury or property damage. This discussion is therefore included both to caution the reader and to prepare the reader for an informed consultation with insurers and legal counsel.

This section will begin with an overview of the legal theories by which claimants may attempt to attach liability to wastewater reclamation projects. No treatment of liability in commercial activities involving public entities may omit a discussion of governmental liability; the narrow protection offered through immunity will therefore be explained. The focus of this section, however, will be upon the scope of liability limitation that may be achieved by contract [30]. A sample of proven liability disclaimer and limitation clauses adapted to the wastewater supply contract is provided in Appendix E.

Several types of liability must be considered in the contractual stage. The claims that concern us are claims for personal injury and property damage due to contamination by reclaimed wastewater. The risk to the irrigator of short-term crop damage is fairly well understood and for this reason can be provided for by contract between the buyer and seller. The potential for injury to third parties is less well understood and less easily dealt with by contract. No adverse health effects have been reported, although there are over 200 wastewater reclamation projects in California, some long established. However, even the remote possibility of mismanagement in effluent application, malfunction in treatment [31], and toxic chemical contamination due to industrial chemical spills or dumping raises a realistic concern that a third party personal injury or property damage claim may be brought against some wastewater facility [32].

Proof of damage to the claimant and of a causal connection to the activities of the party to be held responsible are prerequisites to a successful suit. For some types of damage associated with wastewater reclamation the proof may be relatively simple, as where reclaimed wastewater comes into contact with a crop on which its use is not approved. In such a case, the owner may suffer an immediate loss of marketability. Generally the association between observed damage and the use of reclaimed wastewater for irrigation will be difficult to establish. However, there is no room for complacency. A similar problem of proof exists in establishing damages due to personal exposure to environmental hazards in the workplace and due to the ingestion of slow-acting medicinal toxins. The law developing in these areas suggests a trend toward relaxing some of the traditional obstacles barring recovery. Courts show an increasing reluctance to bar suits because of statutes of limitation, and an increasing willingness to infer responsibility for damage by means of circumstantial evidence [33]. We will assume that our hypothetical claimants are able to prove actual damage causally connected to the use of reclaimed wastewater for irrigation.

Legal Theories Supporting Liability in the Sale of Treated Wastewater

Negligence

A person is negligent when he fails to take those precautions a reasonable person would take to protect others from foreseeable risks arising from his activities. The violation of a statute or administrative regulation designed to protect against a particular risk of harm raises a presumption of negligence and exposes the violater to liability for any injuries to a member of the class intended to be protected [34]. If any of the quality criteria or management regulations are violated in the treatment, delivery, or application of reclaimed wastewater, negligence would be presumed. Violation of the treatment standards would raise a presumption of negligence against the wastewater treatment facility. Violation of management standards in the application of the water would raise a presumption only against the irrigator, unless the treatment facility had violated a specific duty to inspect the irrigation operation [35] or was negligent in entrusting the wastewater to this operation. The statutory standard is no more than a minimum; the wastewater treatment facility may still be negligent if special circumstances raise foreseeable dangers beyond those provided for in the standard. An example of special circumstances might be unusual subsoil characteristics at the irrigation site that make surface irrigation inadvisable because of the risk of polluting groundwater.

Strict Liability in Tort

Anyone injured by a defective product may hold the manufacturer and all parties engaged in putting the product on the market strictly liable for his injury [36]. No proof of negligence or other wrong-doing is required [37]. This product liability theory recognizes two types of product defect: manufacturing defects and design defects. A manufacturing defect in treated wastewater might be found if it failed to meet the regulatory water-quality standards; a design defect might be found if water that met all applicable water-quality standards nonetheless caused damage, as by residual salt concentration or boron toxicity [38].

Strict liability applies only to the manufacture of goods. It is not imposed upon businesses providing services in which defective goods may incidentally be employed. No case has been reported characterizing reclaimed wastewater, but because a wastewater reclamation facility processes and sells the water for commercial use by others, it is more likely to be found a manufacturer of goods than a mere provider of services [39].

Warranty

If wastewater is considered a commercial good, then injured parties may hold wastewater suppliers liable for breach of warranty [40]. There is some opinion that structuring the supply contract as a lease instead of a sale will avoid warranty liability. This is questionable. A court is free to look to the real character of a transaction; where it finds that the product "leased" is consumed, it is unlikely to allow this subterfuge [41].

A sure prevention of warranty liability is to limit the number of warranties provided. Unfortunately for the supplier, warranties are more easily created than avoided. Any sample, model, or description of the goods will create an express warranty. The state's wastewater Reclamation Criteria and Regional Water Quality Control Board requirements, as well as any informal assurances of safety, would be considered express warranties of quality [42]. Moreover, the law will imply certain warranties without any specific representations by the seller, such as the implied warranty of merchantability [43] and the implied warranty of fitness for a particular purpose.

The implied warranty of fitness for a particular purpose is of special concern in irrigation with reclaimed wastewater. It arises when the seller has reason to know that the buyer intends to use the goods for a particular purpose, and that the buyer is relying on the seller's skill and judgment to furnish suitable goods. An implied warranty of fitness for the known intended use would arise in every wastewater supply contract because of the necessarily detailed knowledge of the buyer's use and because of the active role in advising the buyer which is imposed by law upon the treatment facility.

Although anyone damaged by breach of express warranty may sue the seller, breach of an implied warranty may only be asserted by the party with whom the contract was made [44]. By complying with certain formalities, the seller in commercial transactions has considerable room to reduce exposure to both kinds of warrant liability.

Governmental Immunity

Where wastewater reclamation is conducted by public entities, the liabilities of the preceding section are subject to procedural limitations and immunities found under the California Tort Claims Act [45]. The Act provides that public entities are not liable for injuries except as permitted by statute [46]. Most of this immunity is then withdrawn. Public entities are fully liable in suits based upon contract [47] or workers' compensation [48]. The following governmental immunities are limited to personal injury and property damage claims not based upon contract.

Liability From Inadequacy of Standards

Public entities and their employees are immune from liability for any injury resulting from the adoption, non-adoption, or failure to enforce any statute or regulation. The state and the Department of Health Services cannot be held liable if the wastewater treatment standards prove insufficiently rigorous. It has been speculated that this immunity may also shield entities directly involved in wastewater reclamation from liability for failure to enforce those standards [49]. This is unlikely, as the California Supreme Court has ruled that this statutory immunity is confined to quasi-legislative and law enforcement agencies. It is specifically withheld from public entities which are charged by law with a regulatory duty designed to protect the public against particular injuries [50]. A public licensing entity which must require compliance with certain health and safety regulations will be liable if it grants approval to applicants who do not meet the regulatory standards [51]. Similarly, an entity charged with a specific duty of ongoing regulation will be liable if it fails to regulate.

Liability From Failure to Inspect

Public entities and their employees are generally immune from liability for injuries resulting from a failure to inspect any property to determine if the property meets applicable safety statutes [52]. A public reclamation entity should not be liable for failure to detect unsafe conditions that arise after the approval of a private irrigation site. This immunity would be overridden, however, by a specific statutory duty to inspect.

Liability From the Acts of Employees

Public entities may be vicariously liable for the acts of their employees except where the employees themselves are immune [53]. Generally, public employees are liable to the same extent as private employees [54], but the Tort Claims Act immunizes them when they must exercise discretion. The scope of this immunity is not large. It is confined to policy-making decisions involving a conscious weighing of the risks and advantages of a particular course of action [55]. Furthermore, immunity only extends to injuries that are a direct result of the decision; actions taken to implement it are not shielded. As an illustration, the decision that a particular type of irrigation can be done safely with treated wastewater would clearly be discretionary. The decision that a particular irrigation site could use treated wastewater safely may also be discretionary. Lower-level decisions and activity in actually providing the wastewater to the site would not be immune from liability. Discretionary immunity covers plans and designs for construction or improvement to public property [56]. This would bar suits based on faulty wastewater treatment plant design, not suits based on negligent use or maintenance.

The role of governmental immunity in preventing liability for injuries caused by irrigation with treated wastewater is very restricted. In actions based on contract it is nonexistent. For most situations, the public entity will be as exposed to liability as a private entity.

Procedural Limitations to Public Entity Liability

The more significant protection offered by the Tort Claims Act is found in its requirement that no claim may be pursued in court unless it has first been presented to the appropriate public entity [57]. Many claims are settled or dropped at this stage. The Act also shortens the time for bringing a claim. Claims for personal injury, property damage, or damage to growing crops must be filed within one hundred days after the claim accrues, as opposed to a one-year filing period for suits against private defendants. Other claims, including contract claims, must be filed within one year, whereas in private actions, suits based on contract have a four-year period [58].

Contractual Limitation of Liability

Negligence

The supply contract can minimize the treatment facility's exposure to negligence claims. It does this by clarifying the division of management responsibilities between the parties in the contract and by preserving evidence that the user was fully instructed in all regulatory requirements. The treatment facility must bear all liability resulting from negligence in meeting the treatment standards [59], but the contract can insulate it from risks related to the management of on-site application by specifying the operations and facilities that are under the exclusive control of the user. Most of the contracts reviewed in preparing this material divided responsibilities with satisfactory specificity. A few contracts stated particular off-site contamination risks and set forth management practices required to minimize these risks [60]. Many contracts appended the Health Services Guidelines and the requirements of the Regional Water Quality Control Board to the contract and incorporated them, by reference, into the provisions listing the user's responsibilities. This is recommended.

Strict Liability in Tort

Two defenses to this form of liability will be mentioned here, because they must be prepared in the reclaimed-wastewater-supply contract: the defenses of misuse and express assumption of the risk.

Misuse. A manufacturer is not responsible for damages resulting from unintended, unforeseeable, and abnormal use of his product. Courts are more likely to absolve a manufacturer from liability for the misuse of his product if the proper use is spelled out in the sale contract [61]. The wastewater supplier's duty to instruct the user should be satisfied by attaching the appropriate regulatory guidelines to the contract and specifying any additional management practices necessitated by particular hazards associated with the proposed site, manner of application, or crop.

Assumption of the risk. A manufacturer is not responsible for damage resulting from risks assumed by the buyer. Statute forbids assuming the risk of noncompliance with standards imposed by law upon the facility [62], but the risk of what we have termed design defects (damaging qualities in water that meets all regulatory standards) may be assumed. This is a limited defense. It does not prevent recovery by third parties injured by the defect. It does not cover unknown hazards; the buyer must have knowledge of the particular risk, understand the magnitude of the risk, and voluntarily assume it [63].

A buyer who signs a contract containing a broad statement that he agrees to assume all risks and accept all liability will probably not be found to have assumed the particular risk that resulted in damage. If the supplier wishes to avoid liability for design defects by an assumption clause, all risks known to be associated with the chemical composition of the effluent supply and the proposed crop should be stated in the contract and referred to in the assumption clause so that it is clear that the buyer expressly assumes those risks [64].

Warranty

The California Commercial Code allows sellers to limit their liability for breach of warranty by disclaiming, modifying, or excluding warranties [65] and by limiting the remedies available upon breach [66].

Disclaimer. Unintended oral warranties as well as implied warranties may be disclaimed in the supply contract. The term "merchantability" must be used to disclaim the implied warranty of merchantability [67], but otherwise no particular language is required; unintended oral warranties and implied warranties of fitness for a particular purpose may be excluded in most contracts if the contract merely states, "There are no warranties that extend beyond the description on the face of this contract" [68].

However, for any disclaimer to be upheld against the buyer there must be no question that it was brought to his attention. Courts enforce this requirement of conspicuousness with zeal. To disclaim the implied warranties, a disclaimer must be set out from the contract in bold-face type or markedly contrasting color [69]. Furthermore, mere notification of a broadly worded disclaimer will not suffice unless the buyer understands the nature of the risk he will incur [70]. Because the processing of wastewater for use in irrigation is highly technical, requires compliance with a complex body of regulations, and involves subtle potential for damage not likely to be foreseen by the businessman-farmer, disclaimers in these contracts are particularly susceptible to judicial disapproval. Care must be taken to notify the buyer of the scope and import of any warranty disclaimer. Any doubt will be resolved against the seller.

Some warranties may not be disclaimed. Compliance with regulatory wastewater-quality standards is probably an undisclaimable warranty [71].

Limitation of remedies. The Commercial Code allows sellers to reduce their exposure to liability for breach of warranty by specifying the remedies available to the buyer [72]. Courts do not view the limitation of remedies with the disfavor shown disclaimers, possibly because the seller appears to be promising some remedy rather than avoiding all remedy. The public policy against disclaiming warranties created by law does not apply to limiting remedies for the breach of such warranties [73]. The code does give the buyer some protection. The remedy provided in the contract will be optional unless the contract states that it is to be exclusive; moreover, even an "exclusive" remedy will be treated as optional unless it gives the buyer the substantial value of his bargain [74]. The tolerance of the courts to the repair or replace remedy in the sale of consumer goods, where courts otherwise have been protective of the buyer, indicates this substantial value requirement is not a great obstacle [75]. A truly bargained limitation can allow the parties to achieve an approximation of a fair sharing of the unknown risks in their business relationship. The parties who know the commercial context must determine what is reasonable.

The contract may also limit the time period in which a claim may be brought to court by the buyer. The statute of limitations for warranty actions against private defendants is four years under the commercial code, but it may be shortened by agreement to one year [76]. Because any crop damage suffered by the buyer should be apparent at the end of one growing season, providing a one-year statute of limitations should be fair to the buyer, yet would protect sellers against stale claims upon past damages for which rebuttal evidence would not be available [77].

Indemnification

The wastewater reclamation facility may reduce its exposure to liability in the supply contract, but it cannot altogether eliminate it. The preceding contractual devices can bar or limit many claims that might be asserted by the buyer. They are less effective obstacles to third-party claims [78]. Bearing primary liability does not require paying damages, however. The wastewater supplier may require in the contract that the water user indemnify it against third-party liability [79]. An agreement to indemnify is an agreement by one contracting party to pay claims brought against the other party. The parties may agree to indemnification against some or all hazards. They may even provide for indemnification against damages resulting from negligent violations of law [80], such as failure to meet the regulatory water-quality standards, but such an agreement must be explicit, because any doubt will be resolved against the supplier [81].

The ability of the water supplier to avoid payment of damage claims by indemnification depends upon the ability of the water user to pay and upon the enforceability of the indemnity clause. An agreement to indemnify is a contract between potential defendants. It does not limit the recovery of the injured party. If the water user is unable to pay, the water supplier will be responsible for the full amount of the claim. For this reason, it is essential to make the wastewater supply contract contingent upon the water user obtaining adequate insurance. The enforceability of an indemnification clause will depend upon the general principles of contract law discussed in the next section.

Public Policy Restraints on Avoiding Liability by Contract

Certain formal rules restraining liability avoidance through the contractual devices of assumption of risk, warranty disclaimer, and indemnification have been mentioned. These are: the rule requiring actual notice to the buyer by conspicuous and clear language, the rule requiring understanding assent by the buyer, and the rule requiring terms by which the buyer accepts liability to be interpreted strictly against the seller. In addition, there is a general principle of protection against unfair dealing which will invalidate many provisions limiting liability that are formally correct.

Under the common law doctrine of unconscionability, a court may refuse to enforce a contract in which there was an absence of meaningful choice for one of the parties, coupled with terms unreasonably favorable to the other party [82]. The Uniform Commercial Code explicitly adopted this common law rule; the California Commercial Code did not. The status of the doctrine in the enforcement of commercial contracts in California is therefore uncertain. While not basing their decisions upon unconscionability, California courts have frequently mentioned the doctrine as an alternate ground of decision when they have struck down terms "oppressive" to the buyer. It appears that the doctrine is alive and well beneath the surface of these decisions and should inhibit any seller from attempting to impose terms too one-sided to his benefit [83].

Courts are particularly protective of the buyer when they determine that the sales contract is an adhesion contract. An adhesion contract is one in which the buyer has little opportunity to bargain for favorable terms. This situation typically arises when a buyer has a need for particular goods and limited ability to seek an alternative supply, or when all the sellers in the market for those goods rely on similar contracts. When an adhesion contract is found, the courts will scrutinize any clause shifting liability to the buyer to determine whether the buyer gave understanding and voluntary assent. Courts have refused to enforce provisions unquestionably brought to the buyer's attention when they have determined that there was little opportunity for real bargaining and that the provisions defeated the reasonable expections of the buyer [84].

A contract for the sale of reclaimed wastewater, at least to agricultural irrigators, may have some of the ingredients of adhesion: the goods sold may be a commercial necessity in water-short times, and supply may be so limited geographically that the buyer has little ability to shop. Although the present abundance of fresh water as an alternative supply argues against adhesion, it is prudent to bear in mind the possibility of this interpretation; care should be taken to preserve in the contract some evidence of understanding bargaining over the terms allocating financial responsibility for damages to the buyer.

Conclusion

One writer has suggested that a wastewater supply contract most likely to minimize the possibility of future third-party liability is one that allocates financial responsibility according to the control of each party over the potential source of damage. The theory is that financial responsibility is necessary to promote caution. Under such a contract, all risks associated with wastewater treatment and with delivery to the user's headgate would be borne by the water supplier. All risks associated with the proper application of the water after delivery would be borne by the water user. To make the obligations of each party clear, the contract would specify all regulatory guidelines appropriate for the proposed use [85]. To achieve the separation of liability, express warranties, disclaimers of warranty, and assumptions of risk would be employed to bar claims by each party for damage resulting from elements within his control. Cross-indemnification agreements would similarly allocate responsibility for insuring against liability toward third parties. This is the approach apparently preferred by the few supply contracts reviewed that dealt with liability in some detail [86]. It has much to recommend it.

In some other enterprises, however, the apportionment of liability is treated solely as a matter of economics; the price of the product bears the cost of insuring against its hazards. A rational goal under this approach is to concentrate the cost of insurance upon the buyer to the extent that it can be done and preserve the competitiveness of the product. This section concludes by reviewing the devices by which the obligations of the seller toward the buyer can be clarified, the liability toward the buyer can be minimized, and the responsibility for insuring against third-party liability can be concentrated on the buyer.

To minimize points of litigation between the parties to the contract, all warranties intended should be expressed in writing. The statutory wastewater treatment standards are certain to be among these. All other warranties should be disclaimed as required by the Commercial Code: in writing and conspicuously. It is prudent to have the buyer initial the disclaimers. Particular mention should be made of any known and unavoidable risks. The buyer should expressly assume these.

The parties should also agree upon a limited remedy in the event a warranty is breached. For private water suppliers, a separate clause should be included limiting the time within which an action for breach of warranty may be brought, not less than one year from breach.

If the supplier wants to concentrate all responsibility for insuring against third-party liability on the buyer, the contract should provide that the buyer agrees to indemnify the supplier against any and all liability arising from the use of treated wastewater for irrigation. It should specifically state that the buyer will indemnify the supplier even if the cause of damage is active negligence by the supplier. The contract should provide that it is the obligation of the buyer to obtain insurance; it should be contingent upon proof of insurance.

The goal of a contract is to keep the parties out of court. This is most likely to be achieved when the obligations of the parties are clearly understood and when there is a sense of fair dealing. These are also the most important factors in determining whether a contract will be enforced in court. Whether it is reasonable, fair, or advisable to impose the burden of financial responsibility upon the buyer to the fullest extent possible depends upon the economic circumstances surrounding the particular wastewater supply contract. A very different allocation may be advised. It is certain, though, that if the risks are not realistically appraised and bargained for to preserve the reasonable expectations of the parties, the contract will be rewritten in court.

NOTES

1. People v. City of Roseville, Civil No. 49608, Cal. Super. Ct., Placer County, Sept. 30, 1977. The City of Roseville contracted to sell treated wastewater to certain irrigators in the drought year of 1977. For many years it had released its effluent into Dry Creek after treatment. The SWRCB brought an action to enjoin the sale because the withdrawal of the water would injure other legal users downstream.
2. Ling, C. 1978. Wastewater Reclamation Facilities-Survey 1978. Sanitary Engineering Section, Department of Health Services, Berkeley, Calif.
3. Governor's Commission to Review California Water Rights Law, final report, at 63-65 (December, 1978).
4. Cal. Water Code Section 1210 (West Supp., 1984).
5. Cal. Water Code Section 1210 (West Supp., 1984).
6. Cal. Water Code Section 1211 (West. Supp., 1984), Section 1700 et seq (West, 1971). By approving the diversion of the treated wastewater under this procedure, the SWRCB is not granting the treatment facility an appropriation permit. For the difficulties that may result from using this abbreviated procedure instead of applying for an appropriation permit, see ensuing discussion under Rights to Reclaimed Water.
7. A riparian right may be quantified and given a priority date in a statutory adjudication proceeding. This time-consuming and expensive process has only been accomplished for a few small stream courses. See Cal. Water Code Sections 2500 et seq (West, 1971; West Supp., 1984).
8. No more than a skeletal treatment of these water rights can be given here. For a thorough yet reasonably concise study, the reader is referred to the reports issued by the Governor's Commission to Review California Water Rights Law (published May, 1977-January, 1978).
9. The definitive cases establishing the priority of riparian over appropriative rights are Lux v. Haggin, 69 Cal. 255, 10 P. 674 (1886); Herminghaus v. S. Cal. Edison Co., 200 Cal. 81, 252 P. 609 (1926).

10. Joslin v. Marin Municipal Water Dist., 67 Cal. 2d 132, 429 P. 2d 889, 60 Cal. Rptr. 377 (1967).

11. A 1923 amendment to the Water Code made the permit system the exclusive means of obtaining a water right.

12. Cal. Water Code Section 1201 (West, 1971). For permit procedure see Title 23, Cal. Admin. Code, Chapter 3, Subchapter 2.

13. Cal. Water Code Section 5101 (West Supp., 1981).

14. Cal. Water Code Section 1701 (West, 1971).

15. Cal. Water Code Section 1702 (West, 1971).

16. Cal. Water Code Sections 106.5, 1203, 1460-1464 (West, 1971).

17. Cal. Water Code Section 10500 (West Supp., 1984).

18. Cal. Water Code Section 1460 (West, 1971): a municipal use is the use of water for the municipality or its inhabitants for domestic purposes. See also 23 Cal. Admin. Code Section 664 (Oct. 13, 1979), Municipal Uses, and 23 Cal. Admin. Code Section 661, Domestic Uses. Under Cal. Water Code Section 1463 (West, 1971), a municipality is allowed to appropriate an amount of water beyond its present municipal needs, provided that others may obtain temporary rights to the surplus. When the municipality expands its water consumption, it must compensate those temporary users for facilities rendered valueless by the withdrawal of water. In addition to this statutory municipal right, there is a common-law municipal right which may be asserted by former Spanish pueblos. Because of its limited applicability, it is not discussed in this chapter.

19. Telephone interview with Carol Atherton, Assistant Chief, Division of Water Rights, State Water Resources Control Board (March 23, 1982).

20. Cal. Water Code Sections 1210 to 1211 (West Supp., 1984); Cal. Water Code Sections 1700 et seq. (West, 1971).

21. The procedure for obtaining an appropriation permit is set forth at Cal. Water Code Sections 1300 et seq (West, 1971). The major differences in procedural burden between the two options are in the requirements of the application and notice. The permit application generally requires more information than the change petition (including maps and drawings of the proposed diversion).

Whereas a notice procedure is prescribed by statute for a permit application, the Board has discretion under the change procedure to enlarge or attenuate notice. Those differences will disappear where it is apparent to the Board from the size of the proposed reclamation project, or from the particular circumstances of the reclamation locale, that other water users are likely to be affected. Moreover, if protests are filed against a change petition, there will probably be no savings in time to recommend the change petition over a permit application.

22. Stats. 1915, c. 91, now Cal. Pub. Util. Code Section 1501 et seq, (West, 1975).

23. Cal. Pub. Util. Code Sections 1505, 1505.5 (West, 1975). Under another recent amendment to the Water Code, public utilities are prohibited from supplying water to any land within a municipal water district subject to indebtedness for water bonds, as long as the district is ready, willing and able to serve the land, unless a majority of the voters consent at a special municipal water district election. Cal. Water Code Section 71699 (West Supp., 1981). This appears to prevent the sale of water even if the municipal entity consents. This restriction might be circumvented if the municipal entity resolves that it is not "ready, willing and able" to serve the target area.

24. Cal. Pub. Util. Code Section 1503 (West, 1975).

25. Cal. Pub. Con. Code Section 20802 (West, 1984).

26. It may be argued that the placement of this provision in the Health and Safety Code, under the powers of sanitary districts, indicates that the legislature was concerned with assuring an uncontaminated water supply, not with restraining wastewater competition. The provision does not state that compensation may be a condition to consent, nor does it refer to those sections of the Public Utility Code requiring compensation.

27. The experience of the Carmel Sanitary District demonstrates that this problem is not merely theoretical. CSD has contracted to supply treated wastewater to golf courses within the service area of the Cal American Water Company. Cal American raised vigorous objection to the contracts, asserting that it has facilities that

will go unused if treated wastewater is supplied. Negotiations were suspended pending grant approval for the CSD project at the date of this writing. Interview with Mike Zambory, General Manager, Carmel Sanitary District (March 25, 1982; April 13, 1983).

28. Cal. Water Code Section 13550 (West, Supp. 1984): "The Legislature hereby finds and declares that the use of potable domestic water for the irrigation of greenbelt areas, including, but not limited to, cemeteries, golf courses, parks, and highway landscaped areas, is a waste or an unreasonable use of such water...when reclaimed water... is available..."

29. Interview with Richard Mills, Water Resources Control Engineer, Office of Water Recycling (March 9, 1982).

30. See Brown, E. C., and N. Weinstock, Legal Issues in Implementing Water Reuse in California, 9 Ecology Law Quarterly 243, 278-292, for a more extensive discussion of the applicability of these theories of liability to wastewater reclamation projects.

31. See note 2. Ling, C. Wastewater Reclamation Facilities Survey 1978.

32. The safety record of reclamation projects is excellent. Based on this record, casualty underwriters consider the risk of third party claims to be low; irrigators have not reported difficulty in expanding their insurance coverage to include these risks. It is not the purpose of this chapter to spread alarm, but to add by contractual foresight to the margin of safety already created by sound reclamation practices.

33. Sokol, M., Statutes of Limitations and Pollutant Injuries: The need for a Contemporary Legal Response to Contemporary Technological Failure, 9 Hofstra L. Rev. 1525 (1981). *Res ipsa loquitur* is the theory of proof which legal theorists propose to apply to overcome the difficulty of determining the responsibility of individual sources in pollution injury suits. It is codified in Cal. Evid. Code Section 646 (West Supp., 1984). Under this theory, a presumption of negligence is raised whenever it can be concluded that a particular accident would not occur without negligence by someone and that the defendant is probably

the one responsible. It is undergoing rapid expansion in the field of medical products liability, where it has been used to attach liability to entire sectors of the pharmaceutical industry. Sindell v. Abbott Laboratories, 26 Cal. 3d 588, 607 P. 2d 924, 163 Cal. Rptr. 132 (1980) (liability of manufacturers of diethylstilbesterol). It may not be expanded to wastewater reclamation, however, for two reasons: it has traditionally been considered inapplicable to new industries because not enough is known about hazards of non-negligent operation; it is questionable in wastewater reclamation because of the number of factors that could lead to contamination despite due care. See Brown and Weinstock, Legal Issues, supra, note 30, for citation of cases in which res ipsa loquitur was used to establish negligence in the supply of fresh water.

34. Byrne v. City and County of San Francisco, 113 Cal. App. 3d 731, 170 Cal. Rptr. 302 (1980); Vesely v. Sager, 5 Cal. 3d 153, 486 P. 2d 151, 95 Cal. Rptr. 623 (1971).

35. See discussion under govenmental immunity. In general, negligent inspection of property does not give rise to liability against public entities.

36. Recovery may be obtained not only for personal injuries but also for injuries to property alone, such as crop damage. Purely economic injury, such as loss of bargain due to the reduced value of the water, is not recoverable under this theory. Seely v. White Motor Co., 63 Cal. 2d 9, 19, 403 P.2d 145, 45 Cal. Rptr. 17 (1965); Gherna v. Ford Motor Co., 246 Cal. App. 2d 639, 649, 55 Cal. Rptr. 94 (1965); Elmore v. American Motors Corp., 70 Cal. 3d 578, 451 P.2d 84, 75 Cal. Rptr. 652 (1969).

37. Greenman v. Yuba Power Products, 59 Cal. 2d 57, 377 P.2d 897, 27 Cal. Rptr. 697 (1963).

38. In determining whether a design is defective, the benefits of the design are weighed against the risk of harm it presents. Barker v. Lull Engineering Co., 20 Cal.3d 413, 573 P.2d 443, 143 Cal. Rptr. 225 (1978). Because properly produced wastewater creates economic benefits that should outweigh the cost of isolated instances of damage, it is possible that courts would

not find its "design" defective; in this case, strict liability would not be applied. Negligence and warranty theories remain. A third type of product "defect" is being introduced into strict products liability from the law of negligence, through a combination of medical malpractice and product liability. Under this theory, a product (such as a drug) that is not defective in either manufacture or design may still be deemed defective because of a failure to give adequate warning of potential hazards. Fogo v. Cutter Laboratories, Inc., 68 Cal. App. 3d 744, 137 Cal. Rptr. 417 (1977). This is conceivably applicable to the sale of reclaimed wastewater. The Health Services Guidelines should satisfy any requirement of adequate direction and warning, however.

39. Reclaimed wastewater may have been deemed a "good" for the purposes of warranty law. See below, note 40, Voth v. Wasco Public Utility District.

40. Fogo v. Cutter Laboratories, Inc., supra, 68 Cal. App. 3d 744, note 38. Warranty law is governed primarily by the California Commercial Code, Sections 2312-2317 (West, 1964). The definition of goods in the code does not preclude wastewater (Section 2105: "all things moveable at the time of identification to the contract for sale..."), but there is no definitive court decision. One case appears to accept the applicability of warranty theory to a claim for wastewater damage to crops, but the issue was not directly decided by the court. Voth v. Wasco Public Utility District, 56 Cal. App. 3d 353, 128 Cal. Rptr. 608 (1976).

41. Voth v. Wasco Public Utility District, supra, 56 Cal. App. 3d 353, note 40, at 359, indicates that reclaimed wastewater supplied as part of the lease of a wastewater treatment district's land would be subject to the warranty provisions of the code.

42. It is not necessary for the buyer to have relied upon these assurances as the basis of the bargain. Any representation of fact by the seller becomes woven into the "fabric of the agreement." Hauter v. Zogarts, 14 Cal.3d 104, 115, 534 P.2d 377, 120 Cal. Rptr. 681 (1975).

43. The implied warranty of merchantability arises when the seller is a merchant dealing in goods of the kind sold by the contract in question. There is little doubt that if reclaimed wastewater is a good, the facility selling it will be deemed a merchant. See Brown and Weinstock, Legal Issues, supra, note 30, at 282. This warranty is violated if the reclaimed wastewater is not fit for the ordinary purposes of irrigation. Wastewater that meets the regulatory quality standards should satisfy the warranty of merchantability.

44. Hauter v. Zogarts, supra, 14 Cal. 3d 104, note 42, at 119-120.

45. Cal. Gov. Code Sections 810-996.6 (West, 1980).

46. Cal. Gov. Code Section 815 (West, 1980). Public entities include the State, the Regents of the University of California, counties, cities, districts, public authorities, public agencies, and any other political subdivisions or public corporations in the State. Cal. Gov. Code Section 811.2 (West, 1980). A sanitary district is a public entity. Ambrosini v. Alisal Sanitary District, 154 Cal. App.2d 720 (1957).

47. Cal. Gov. Code Section 814 (West, 1980). This section also provides that nothing in the code affects liability for other than money damages. Suits for injunctive or declaratory relief may always be brought.

48. Cal. Gov. Code Section 814.2 (West, 1980).

49. See Brown and Weinstock, Legal Issues, supra, note 30, at 290-291.

50. Cal. Gov. Code Section 815.6 (West, 1980).

51. Morris v. County of Marin, 18 Cal. 3d 901, 559 P.2d 606, 136 Cal. Rptr. 251 (1977) (county liable for failing to ascertain before issuing building permit that contractors carried adequate workers' compensation insurance. Such insurance was a prerequisite to a building permit. The county had no discretion to waive it.) The key is whether the regulatory body has discretion to allow the activity to proceed whether or not the statutory standard is met.

52. Cal. Gov. Code Sections 818.6, 821.4 (West, 1980). This does not apply to the entity's own property.

53. Cal. Gov. Code Section 815.2 (West, 1980).
54. Cal. Gov. Code Section 820 (West, 1980).
55. Johnson v. California, 69 Cal.2d 782, 447 P.2d 352, 73 Cal. Rptr. 240 (1968).
56. Cal. Gov. Code Section 830.5 (West, 1980).
57. Cal. Gov. Code Section 945.4 (West, 1980).
58. Cal. Gov. Code Sections 910-913.2 (West, 1980). The accrual of the claim is governed by the same factors as the accrual of claims against private parties. Cal. Gov. Code Section 901 (West Supp., 1984). This may lead to considerable extension of time, since personal injury or property damage claims do not accrue until with reasonable diligence they should have been discovered. In the DES suit, this was twenty and more years. In addition, if the claim for property or crop damage is based upon contract, the longer contract period will apply, rather than the injury period. Voth v. Wasco Public Utility District, supra, 56 Cal. App. 353, note 40.
59. Cal. Civ. Code Section 1668: Contracts contrary to policy of law (West, 1973).
60. Lease agreement of the City of Lodi, 1976; lease agreement between Lake Arrowhead Sanitation District and Hesperia Enterprises, Inc., 1977; Agreement for Allocation of Costs and Use of Reclaimed Water between Carmel Valley County Sanitation District and Carmel Valley Ranch, 1981.
61. Erickson v. Sears, Roebuck & Co., 240 Cal. App.2d 793, 59 Cal. Rptr. 143 (1966) (stepladder sold with instructions not to use on soft surfaces); Garcia v. Joseph Vince Co., 84 Cal. App.3d 868, 148 Cal. Rptr. 843 (1978) (fencing mask sold for use with blunt foils). The rationale of this defense is that it is the unforeseeable action of the user, not a defect in the quality of the product, that is the cause of the injury.
62. Cal. Gov. Code Section 815.6 (West, 1980). See discussion under governmental immunity.
63. Smith v. Dhy-Dynamic Co., 31 Cal. App. 3d 852, 107 Cal. Rptr. 907 (1973).

64. A prudent irrigator would probably object to an assumption clause completely exculpating the facility from any responsibility for not meeting the agreed non-statutory quality standards. The contract used by the City of Petaluma in 1981 suggests an equitable division of the risk. In this contract, the facility agrees to notify the buyer if the water fails to meet specified chemical standards. The buyer assumes the risk only of that damage occurring after notification.

65. Cal. Com. Code Section 2316 (West, 1964).

66. Cal. Com. Code Section 2719 (West Supp., 1984).

67. The following disclaimer was held sufficient to exclude warranty of fitness, but not warranty of merchantability: "Seller makes no warranty of any kind, express or implied, concerning the use of this product. Buyer assumes all risk in use or handling, whether in accordance with directions or not". Burr v. Sherwin Williams Co., 42 Cal 2d 682, 628 P.2d 1041 (1954).

68. The code also permits disclaimer of all implied warranties by sale "as is" or "with all faults." Cal. Com. Code Section 2316 (3)(a). This is clearly inapplicable to the sale of treated wastewater. However, if in the course of dealing or trade, certain risks are customarily assumed by the buyer, this custom will prevent contrary warranties from being implied. Cal. Com. Code Section 2316 (3)(a). Therefore, if common knowledge and custom place some risks upon the irrigator, it is possible that the supplier will not be held liable for injury resulting from these risks under an implied warranty. It is far safer to express all limitations upon warranties.

69. Dorman v. International Harvester Co., 46 Cal. App.3d 11, 120 Cal. Rptr. 516 (1975) (Disclaimer was ineffective to bar suit on implied warranty of fitness because not sufficiently conspicuous, although it was placed close to where the buyer signed and was in slightly larger type.) The Commercial Code does not require that a disclaimer of express warranties be set out from the body of the contract. It does require notice to the buyer. Because the scope of implied warranties in the sale of treated wastewater is untested, and because these sale contracts are likely to be

construed to the disadvantage of the seller (see following text discussion), it would be wise to ignore this subtle distinction between disclaimers of express and implied warranties and print any disclaimer in bold-face type.

70. Hauter v. Zogarts, supra, 14 Cal. 3d 104, note 42; Dorman v. International Harvester Co., supra, 46 Cal. App. 3d 11, note 69.

71. Cal. Civ. Code Section 1668 (West, 1973): Contracts contrary to policy of law: "All contracts which have for their object, directly or indirectly, to exempt anyone from responsibility for...violation of law, whether willful or negligent, are against the policy of the law." The sixth circuit federal court of appeals, applying California law, held that Section 1668 prohibited disclaimer of an express warranty of seed germination found to arise under the certification standards of the California Seed Law. Agricultural Service Ass'n, Inc. v. Ferry-Morse Seed Co., 551 F.2d 1057 (6th Cir. 1977). See Callahan, The Effect of Warranties on Seed Sales, 11 U.C.D. L. Rev. 335 (1978).

72. Cal. Com. Code Section 2719 (West Supp., 1984): Contractual Modification or Limitation of Remedy. The statute allows the seller to limit remedies sought on a breach of warranty theory. The buyer may still sue on a strict liability or negligence theory. There is a possibility that a remedy limitation clause might also cover negligent breach of warranty, even negligent breach of a warranty imposed by law. Sellers have traditionally not been allowed to disclaim liability for negligence, but in a few decisions involving sophisticated commercial parties, such disclaimers have been upheld. See Delta Airlines Inc. v. Douglas Aircraft Co., 238 Cal. App.2d 95, 47 Cal. Rptr. 518 (1965); Southern Cal. Edison Co. v. Harnischfeger Corp., 120 Cal. App.3d 842, 175 Cal. Rptr. 67 (1981). Although Cal. Civ. Code Section 1668 would prohibit negligence disclaimers involving water quality warranties imposed by law, it is possible that remedy limitation clauses covering negligent breach of these warranties would be upheld, at least in commercial contracts. It

is therefore advisable for the remedy limitation clause to state that it applies to negligent as well as non-negligent breach of warranty.

73. Lemat Corp. v. American Basketball Ass'n., 51 Cal. App. 3d 267, 124 Cal. Rptr. 388 (1975), held that Cal. Civ. Code Section 1668 does not bar shifting the responsibility to pay damages by indemnification because this does not exempt a party from primary liability. The same reasoning would support limitation of remedy, as long as the limitation does not amount in practical effect to an exemption.

74. Cal. Com. Code Section 2719 (West Supp., 1984), Uniform Commercial Code Comment 1.

75. It would seem that the substantial value requirement could be satisfied by limiting damages to the price of the wastewater contract, or possibly even less. In the sale of crop seeds, a commercial activity analogous to the sale of wastewater for agricultural irrigation, the courts have upheld warranty limitations allowing only the return of the cost of the seed, despite damages amounting to the loss of a crop. For another view, see Callahan, The Effect of Warranties on Seed Sales, supra, note 71, in which the author argues against the evidence that under Cal. Com. Code Section 2719 the outcome should be different.

76. Cal. Com. Code Section 2725 (West Supp., 1984).

77. Unlike tort actions, warranty actions accrue at the date of breach, not the date of discovery. Inobviousness of damage would not allow the claimant to extend the statute of limitations in an action under the commercial code. Cal. Com. Code Section 2725 (2) (West Supp., 1984).

78. Seely v. White Motor Co., supra, 63 Cal. 2d 9, note 36, at 17. The seller is always potentially liable to injured third parties under design defect and express warranty theories because the risk assumption and warranty limitation clauses only restrict claims that may be brought by the buyer. In addition, third parties may bring a suit based on negligent treatment or negligent entrustment by the seller.

79. American Motorcycle Association v. Superior Court, 20 Cal.3d 578, 578 P.2d 899, 146 Cal. Rptr. 182 (1978); Rossmoor Sanitation, Inc. v. Pylon, Inc, 13 Cal.3d 622, 532 P.2d 97, 119 Cal. Rptr. 449 (1975).

80. see note 73.

81. S.C.M. Corp. v. U.S. Slicing Machine Co., 73 Cal. App.3d 49, 140 Cal. Rptr. 559 (1977); Rossmoor Sanitation, Inc. v. Pylon, Inc., supra, 13 Cal. 3d 622, note 79. If an indemnity clause does not expressly cover negligence by the indemnified party, it is a "general clause" and will not be enforced if the indemnified party has been more than passively negligent. Passive negligence is mere non-action, such as failure to discover a dangerous condition created by others; active negligence is action creating a dangerous condition. The agreement found in Appendix C of *Evaluation Of Agricultural Irrigation Projects Using Reclaimed Water* (Office of Water Recycling, California State Water Resources Control Board, 1981) contains such a general indemnification clause: "_____ assumes all liability for damage" and "agrees to hold harmless the District...." This would provide for indemnification against passive negligence. Similar provisions purporting to hold a party harmless "in any suit at law," "from all claims for damages," and "from any cause whatsoever" have been ineffective when the party promising to indemnify has proven active negligence by the other party. The disadvantage to a general clause is that it invites litigation by the indemnifying party's insurer over the issue of active negligence.

82. Williams v. Walker-Thomas Furniture Co., 350 F.2d 445 (D.C. Cir. 1965).

83. See Dorman v. International Harvester Co., supra, 46 Cal. App. 3d 11, note 69; Tunkl v. Regents of Univ. of Cal., 60 Cal. 2d 92, 383 P.2d 441, 32 Cal. Rptr. 33 (1963).

84. Beynon v. Gardon Grove Medical Group, 100 Cal. App.3d 702, 161 Cal. Rptr. 146 (1980); Weaver v. American Oil Co., 276 N.E.2d 144 (1971).

85. Benson, Barbara. Agricultural Irrigation with Treated Wastewater in California: Contractual Allocation of Public Health Risks (1982) (not published at date; manuscript on file at U.C. Davis Law Review Office).

86. See for example the lease agreements used by the City of Lodi. Most contracts reviewed did not address the issue of liability. One attempted to shift all responsibility to the buyer/lessee by broadly worded indemnification. If a third-party claim were brought, it is likely that the buyer/lessee's insurer would contest responsibility under an over-broad and unspecific indemnification clause.

CHAPTER 12

FATE OF WASTEWATER CONSTITUENTS IN SOIL AND GROUNDWATER: NITROGEN AND PHOSPHORUS

F. E. Broadbent and H. M. Reisenauer

NITROGEN

Introduction

In wastewater irrigation, the primary concern with respect to nitrogen is the possibility of nitrate contamination of domestic water supplies and the attendant risk of methemoglobinemia in human infants. Although the incidence of methemoglobinemia, or "blue baby disease," in the United States is very low, the Public Health Service has set 10 mg/L nitrate-N as the level that should not be exceeded in drinking water. The risk is based on the possibility of reduction of nitrate to nitrite in the digestive tract of infants below the age of 6 months. Nitrite absorbed into the blood stream can combine with hemoglobin, thereby reducing its capacity to carry oxygen. Older humans are much less susceptible to the disease than are very young infants. Methemoglobinemia is much more common in ruminant animals than in humans, but its occurrence is usually associated with high nitrate concentrations in forage rather than in drinking water.

Aside from the possible risk of groundwater contamination, it is desirable to recycle nitrogen wherever feasible, since it is an essential nutrient required for the production of food and fiber. Its reuse also represents energy conservation.

Forms of N in Wastewaters

Wastewaters typically contain three forms of nitrogen: organic, ammonium, and nitrate; low concentrations of nitrite may also be present. The relative proportions of these various forms varies with the origin and treatment history of the wastewater, but most commonly ammonium (NH_4^+) is the principal form, usually falling in the concentration range of 5 to 40 mg N/L. The organic fraction, which may be either soluble or fine particulates, consists of a complex mixture including amino acids, amino sugars, and proteins. All of these are readily convertible to ammonium through the action of microorganisms in the wastewater or in the soil (where they are even more readily convertible) to which the wastewater is applied. Except in the case of food-processing wastewater, the organic component represents less than half the total N present. Nitrate concentrations may range from 0 to more than 30 mg N/L. Where aerobic treatment processes have occurred, some of the ammonium in the treated water often will have been converted to nitrate through the action of nitrifying bacteria.

N Retention in Soil

Some ammonia may be volatilized from wastewaters with pH values above 7.0. Certain types of clay minerals that commonly occur in California soils, particularly in soils subject to considerable shrinking and swelling during wetting and drying cycles, have the ability to trap ammonium ions within the crystal lattice. Ammonium ions thus fixed are not displaced readily by other cations in the soil solution, such as calcium, magnesium, or sodium, nor are they accessible to nitrifying bacteria. A fraction of any application of ammonic N may be fixed in this way, but over the long term it would not have an important effect on the nitrogen budget.

Like other cations in wastewater, ammonium ions can be adsorbed by the negatively charged clay and organic colloids in soil. Unlike the fixed form, adsorbed ammonium can be readily exchanged by other ions in the soil solution. In all except very sandy soils, the ammonium adsorption capacity of soils is sufficient to retain all ammonium from a single slow-rate application near the surface of the soil. For example, if a fairly high ammonium-N concentration of 50 mg/L is assumed in a wastewater applied at the rate of 3 inches (7.5 cm) to a soil with the fairly low exchange capacity of 10 meq/100 g, only 3.8% of the exchange capacity in the surface 2 inches (5 cm) of soil would be required to retain it. Cumulative buildup of adsorbed ammonium is unlikely to occur. The retention of ammonium ion is always temporary, lasting only a few days or weeks, since the adsorbed ammonium is readily oxidized to nitrate by nitrifying bacteria, thereby being made mobile and capable of rapidly moving away from the adsorption site through mass flow or diffusion.

Application of volumes of water substantially higher than the usual 1-4 inches (2.5-10 cm) per week employed in slow-rate application can result in saturation of the ammonium retention capacity of the soil, in which case ammonium ion may leach to considerable depths in the soil profile.

A mechanism of temporary ammonium retention involves assimilation by soil microorganisms. Net immobilization by microorganisms occurs in the presence of decomposable organic residues of low N content. Where wastewater is applied to land following incorporation of mature crop residues, N immobilization may account for as much as 50 lb/acre (56 kg/ha), but values of 20-40 lb/acre (22-45 kg/ha) are more common. Net immobilization normally occurs only during the first 2-3 weeks of crop residue decomposition.

N Transformations in Soil

Three kinds of soil transformations of the N contained in wastewater are important. The first of these is mineralization:

$$\text{Organic N} \longrightarrow NH_4^+ \qquad [12\text{-}1]$$

This transformation involves a wide range of different microorganisms, both aerobic and anaerobic. As has been noted previously, the relatively low concentrations of organic N are quickly converted to ammonium after application to soil. The sequel to mineralization is nitrification:

$$NH_4^+ + 3/2\ O_2 \longrightarrow NO_2^- + H_2O + 2\ H^+ \qquad [12\text{-}2]$$

$$NO_2^- + \tfrac{1}{2}\ O_2 \longrightarrow NO_3^- \qquad [12\text{-}3]$$

The first reaction is carried out by bacteria of the genus *Nitrosomonas* and its relatives, and the second is carried out by *Nitrobacter* and related species. These bacteria are almost universally present in soils, although populations may be quite low in subsoils or dry sandy soils. Application of wastewaters containing ammonium to such soils will result in a buildup of nitrifying bacteria, although maximum numbers may not be attained for a few weeks. In soils where wastewater is applied regularly, nitrification is normally rapid unless temperatures are very low. Nitrification rates range from 5 to 70 lb N/acre·day (6 to 78 kg N/acre·day). Thus the ammonium in 3 inches of wastewater containing 50 mg NH_4-N/L, equivalent to 34 lb N/acre (38.1 kg N/acre), would be nitrified within a week at most.

Another important transformation of nitrogen in soils is denitrification. Although nitrate is the end-product of the normal series of nitrogen transformations in aerobic soils, it can undergo reduction to N_2O and N_2 if oxygen is limiting and if decomposable organic matter is present to furnish energy for the process. The microorganisms responsible for denitrification are facultative anaerobic bacteria, which normally use oxygen from the air for metabolism, but they can use nitrate as a terminal electron acceptor when concentrations of oxygen are very low. The sequence of products is:

$$NO_3^- \longrightarrow NO_2^- \longrightarrow N_2O \longrightarrow N_2 \qquad [12\text{-}4]$$

Both N_2O and N_2 are gases and may escape from the soil, but N_2 is usually the predominant form.

Denitrifying bacteria are common soil organisms of widespread distribution. Rates of denitrification are controlled primarily by the supply of available organic matter and secondarily by the aeration status of the soil, provided the concentration of nitrate available for reduction is not limiting. Theoretically, 1.3 units of decomposable carbon are required for each unit of nitrate-N denitrified, but somewhat more than this amount is necessary in natural systems, because many other heterotrophic microorganisms compete with denitrifying bacteria for organic substrates. Only in wastewater of high biochemical oxygen demand, such as cannery wastes, is there sufficient organic matter to exert a significant influence on the rate of denitrification. Organic matter in soils is often most abundant near the surface, and its availability is likely to be greater there than in the subsoil. This means that the zone of most active denitrification is apt to be close to the surface. For example, Rolston et al. [1] observed maximum rates of production of N_2O and N_2 within the top 10 cm of soil.

The requirement for oxygen deficiency in denitrification near the soil surface is explained by the observation that virtually all soils may experience temporary or spatially restricted anaerobism. Saturation may occur during irrigation or rainfall with the exclusion of oxygen from the soil pores, or oxygen deficiency may occur in an unsaturated soil in sites where the rate of oxygen consumption exceeds the rate of replenishment, particularly in the smaller pores. Some denitrification has been shown to occur in many soils considered to be well aerated. A layer of impeded drainage in a soil profile favors denitrification.

The quantity of N lost through denitrification may vary from none to more than 90% of that applied, depending on soil properties and water management. In general, coarse-textured, well-drained soils of low organic matter content have a low potential for denitrification loss. Sandy loam and loam soils have a medium denitrification potential, and fine-textured soils such as silt loams, clay loams, and clays have a high potential for denitrification. The presence of a layer of restricted drainage in the profile increases the chances for loss by denitrification. Lund and Wachtel [2] have rated a number of California soils according to their denitrification potential. For practical purposes, denitrification can be disregarded in soils of low potential; however, in soils of medium potential, losses in the 10-20% range can be expected, and in soils of high potential, losses of 20-40% can be expected. Denitrification losses are correlated with frequency of irrigation; hence, better N utilization efficiency (less denitrification) can be obtained with fewer irrigations.

Ammonia Volatilization

Where wastewater is applied by sprinkler irrigation, and to a lesser extent by surface irrigation, some loss of N as ammonia is probable, since wastewaters are typically alkaline in reaction. Henderson et al. [3] suggested that volatilization losses during sprinkler irrigation of water with a pH of 7.5-8.5 would amount to less than 20% of the total applied. The possibility of adsorption of gaseous ammonia on leaf surfaces or soil may further reduce this loss.

Plant Uptake of Applied N

The fate of N in applied wastewater depends heavily on the proportion of nitrate in the downward-moving soil solution, which is intercepted and absorbed by plant roots. For example, Kardos and

Sopper [4] reported that application of sewage effluent to forest and cropland at the rate of 1 inch/week over a period of 6 years did not increase the nitrate-N concentration of soil solution samples above the 10 mg/L Public Health Service standard, but this limit was exceeded when the application rate was 2 inches/week.

A crop does not utilize all of the inorganic N present in the root zone. The fraction of the total amount assimilated depends on the plant, depth and distribution of roots, stage of growth, rate of water movement through the root zone, and other factors. In general, the efficiency of uptake of applied N is seldom much in excess of 50% and is often less. Table 12-1 lists values for N uptake efficiency for a few important crops in California in conventional fertilizer practice, but these values may be somewhat higher than would be obtained with a diffuse and dilute source of N such as wastewater.

Table 12-1. Nitrogen utilization efficiency for some crops in California.

Crop	N application rate (kg/ha)	Uptake of applied N (%)
Corn	180	56
Sugarbeet	135	47
Tomato	112	64
Potato	270	39
Rice	90	34

Another consideration is that a certain minimum concentration of nitrate in the soil solution is required to meet the needs of crops. Broadbent and Rauschkolb [5] reported 10-13 mg/L NO_3-N in the soil solution below the root zone of unfertilized corn plants suffering from nitrogen deficiency. Grasses, especially perennials, tend to be more efficient in N uptake than are row crops. For most crops, part of the plant N will be recycled to the soil and eventually be made available to a subsequent crop. In some instances, accumulation of roots and other crop residues may result in long-term storage of significant amounts of nitrogen in the soil profile as these residues are converted into stable soil humus: for example, long-term application of wastewater to a previously uncropped area near Bakersfield [6] nearly tripled the organic N in the soil profile. However, in most situations, the application of wastewater to crops will not materially alter the organic N level of the soil because of its low content of organic carbon.

From the standpoint of long-term application of wastewater, N input levels should be adjusted to compensate for N removal by the harvested portion of the crop plus expected losses from the system by volatilization and leaching. Total plant uptake of N may greatly exceed crop N removal, particularly in fruit crops. Table 12-2, adapted from Rauschkolb et al. [7] and *Better Crops with Plant Food* [20], gives representative crop yields and crop removals of N and P per ton of yield of the harvested component of a number of crops.

Leaching Losses

Nitrate in wastewater applied to land is subject to leaching if not intercepted by plant roots, immobilized by microorganisms, or denitrified. Leached nitrate may be transported to surface waters by tile drains (if these are present) or by seepage on sloping terrain. Otherwise it will move through the profile into groundwater. The magnitude of leaching losses is dependent on quantity of water applied, evapotranspiration, nature of the crop grown, and soil profile characteristics. The total quantity of N leached is much more significant in terms of pollution hazard than is the nitrate concentration, although most attention is usually given to the 10 mg/L public health concentration standard for drinking water. A small volume of water leached, even though high in nitrate concentration, is of less concern than a large volume of leachate at lower nitrate content, since the latter represents a much greater mass emission of nitrate.

Table 12-2. Crop uptake of N and P in relation to yield of some selected crops.[a]

Crop	Component	Representative yield (ton/acre)	N removal	P removal
			(lb/ton of yield)	
Field crops				
Alfalfa	hay	5.8	65	5.3
Barley	grain	2.0	42	7.2
	straw	2.5	17	2.8
Beans, dry	beans	1.34	78	-
Corn	grain	4.5	33	6.8
	silage	25.0	9	-
	stover	2.0	21	2.3
Cotton	seed	0.85	79	22.4
	stalks	0.63	115	16.0
Oats	grain	1.34	42	-
Rice	grain	3.3	31	-
	straw	3.5	10	-
Safflower	grain	1.34	69	-
Sorghum	grain	2.0	42	6.6
	stover	1.8	21	3.4
Soybeans	grain	1.25	134	12.0
	stover	1.25	46	4.0
Sugarbeets	beets	30.0	4	0.2
	tops	30.0	4	0.4
Wheat	grain	2.0	39	8.0
	straw	3.5	18	2.0
Mixed grass	hay	2.0	47	-
Irrigated pasture		2.0	34	-
Fruits and nuts				
Apricot	fruit	8.0	4	-
Cherry	fruit	4.0	5	-
Grapes	fruit	10.0	2	-
Peach	fruit	16.0	3	-
Pear	fruit	15.0	2	-
Plum	fruit	8.0	7	-
Prune	fruit	8.0	7	-
Almond	nuts	0.9	67	-
Walnut	nuts	1.0	53	-
Grapefruit	fruit	11.0	4	-
Orange	fruit	8.0	5	-
Lemon	fruit	13.0	4	-
Avocado	fruit	2.6	8	-
Olive	fruit	2.1	4	-
Strawberry	fruit	19.0	4	-

Table 12-2 continued.

Crop	Component	Representative yield (ton/acre)	N removal	P removal
			(lb/ton of yield)	
Vegetables				
Broccoli	heads	5.0	13	-
Carrots	roots	19.0	4	-
Potato	tubers	20.0	8	-
Tomato	fruits	25.0	4	0.3
	vines	30.0	3	0.4
Turfgrasses				
Bent		2.2	69	-
Bermudagrass		4.0	63	-
Kentucky bluegrass		2.2	62	-
Fuel crops				
Pulpwood (slash pine)	wood	40 cords	150 lbs/acre	13 lbs/acre
	bark & branches		190 lbs/acre	4 lbs/acre

a Adapted from Rauschkolb et al. [7] and from Better Crops with Plant Food [20].

Letey et al. [8] measured effluent volumes and nitrate concentrations of tile-drainage waters from commercial farms in the Imperial, Coachella, Ventura-Oxnard, San Joaquin, and Salinas valleys of California. They found that nitrate concentrations in effluents were not well correlated with N application rate, effluent volume, or soil profile characteristics. However, the amount of N leached through tile drains was quite well correlated with total water discharge and total N applied. Total mass emissions of nitrate over a given period of time could not be estimated from the nitrate concentrations of the tile effluents. They found emissions to be very low where alfalfa was grown, indicating high efficiency of plant uptake of the applied N.

There is considerable evidence that nitrate is accumulating in groundwater in California, as for example in the study by Nightingale [9]. However, the contribution of surface-applied N to these accumulations is not well defined. Both nitrate concentrations and water movement in soils are subject to a widely ranging spatial variability; consequently, calculations of mass flow of nitrate through the soil are subject to considerable uncertainty. Rible et al. [10] estimated nitrate leaching past the root zone at 83 locations in central and southern California from the equation:

$$N_d = \frac{(NO_3\text{-}N)xD}{10} \qquad [12\text{-}5]$$

where N_d is N drained past the root zone in kg/ha·year, NO_3-N is in mg/L, and D is drainage volume in cm/year.

The value of D was calculated from the product of the volume of water applied and the leaching fraction. Considering data from selected sites where records of water and N inputs were most reliable, they found that mass emissions of N were positively correlated with both N applications and drainage volume, whereas nitrate concentrations were not correlated with either of these factors.

Soil profile characteristics were found to be of major importance in influencing the amount of nitrate moving past the root zone. Lund et al. [11] reported significant correlations between soil nitrate concentrations below the root zone and clay content of the upper soil profile. Soils that have high water infiltration rates tend to be relatively low in organic matter and do not readily develop the anoxic conditions that are conducive to denitrification. Such soils are usually sandy and may have no layers in the profile that restrict water movement. High leaching of nitrate is probable under these conditions, particularly where N applied exceeds crop uptake to any significant degree. On the other hand, clayey soils or soils with clay layers or textural discontinuities in the profile typically have slow water movement and are much more likely to develop the anaerobic conditions that favor N loss through denitrification. Consequently, nitrate usually is leached less from a fine-textured soil than from a coarse-textured one with equal N input. Moreover, the fraction of applied N leached increases with increasing level of N input. This is illustrated by measurements of mass emissions of N from columns of Panoche sandy loam receiving 3 inches (7.6 cm) of wastewater per week over several months. Where the applied water contained 61 mg N/L of NH_4^+-N, the effluent contained nitrate equivalent to 83% of the input N. When the applied wastewater contained 21 mg N/L, only 16% was leached as nitrate [12].

Estimates of the quantity of N leached in a given situation can be made by subtracting N utilized by the crop from the total N applied and then using a reasonable estimate of denitrification loss to adjust the remainder. A guide to the magnitude of these estimates is provided by the soil textural class as noted in the section on nitrogen transformations in soil.

PHOSPHORUS

The use of treated municipal wastewater for irrigating commercial crops is both practical and safe, provided the capacity of the soil-crop system to retain the applied nutrients is not exceeded. Assuming a P content of 10 mg/L, a season's irrigation (3 feet or 0.9 m of water) supplies 81 lb/acre of P (90.7 kg/ha), equivalent to 186 lb/acre (208 kg/ha) of P_2O_5. Although this is not an exceptionally high application rate, it is considerably above the average fertilizer application for the state (Table 12-3), and if applied over several years to a crop with a low P-removing rate (Table 12-2) on a soil of minimal phosphate sorption capacity, ground- or surface-water contamination can result [13, 14].

Table 12-3. Common rates of fertilization in California.[a]

Crop category or crop	Common rate (lb/acre) and (percentage of acreage treated)		
	N	P_2O_5	K_2O
Citrus and subtropical	137 (92)	110 (16)	78 (16)
Field crops	124 (84)	58 (30)	116 (4)
Fruits and nuts	141 (80)	78 (7)	253 (9)
Pasture (not range)	62 (12)	35 (11)	14 (<1)
Turf	523 (92)	124 (73)	247 (77)
Vegetables	167 (96)	86 (82)	60 (57)
Grapes	54 (79)	27 (11)	126 (10)

[a] Adapted from Rauschkolb and Mikkelsen [19].

Phosphates added to soil may be taken up by the crop, accumulated by the solid phase of the soil in sorption and precipitation reactions, or lost from the system in percolating and runoff waters or by erosion. Reactions with the soil and crop removal account for the largest fraction of the added P. Only small amounts--less than 3% of that added annually--have been found in drainage waters. Studies of the reactions of phosphates in agricultural soils have revealed the important roles of the hydrous oxides iron and aluminum, and of calcium. Quantitatively the data are conveniently represented in the form of sorption isotherms, in which the amount of P sorbed under a specific set of conditions is expressed as a function of the concentration of phosphate in the aqueous phase. The simplest of these is the Freundlich isotherm:

$$P_r = kc^{1/n} \qquad [12\text{-}6]$$

where P_r is the amount of P retained at aqueous phase phosphate concentration c, and k and n are empirical constants. Phosphorus retention, however, does not reach equilibrium, as the equation implies, but involves an initially fast reaction followed by a slow transition to a less soluble product. Likewise, the reverse of the retention reaction--the dissolution of retained phosphate--is rapid following the addition of a soluble phosphate; it then slows with time [15].

In spite of the great differences between soils and their capacities to retain P, the nature of retention reactions is remarkably uniform [16], and their extent can be estimated from relatively simple relationships. Ryden and Pratt [17] have utilized this characteristic in developing a model for predicting the useful life of a field filtering system. The capacity of the system to retain phosphate is determined from measurement of the P sorption capacity of the soil, the amount of P supplied in the wastewater, and the amount removed in the harvested crop. Evaluations of the model [18] have indicated that it satisfactorily predicts the capacity of soils to retain phosphate and thus allows estimation of the maximum useful life of acid-soil systems. It does not provide estimates of phosphate additions to deep percolating and drainage waters from desorption reactions and from preferential transport of soil solution through macropores. A recent review of data from field sites where wastewater irrigation has been practiced for an extended period (21) indicated only infrequent incidences of significant P penetrations into subsoil layers. Because of the many uncertainties involved and the lack of a single standard for acceptable ground-water phosphate levels, sites should be monitored frequently, particularly as P additions approach the estimated capacity.

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