WATER PENETRATION PROBLEMS IN CALIFORNIA SOILS

DIAGNOSES AND SOLUTIONS

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Foreword

This manual is designed to help the farmer, farm advisor, and consultant prevent, diagnose, and solve problems of slow water penetration. It applies research where appropriate but makes no effort to compile research thoroughly. Although there is much research in this area, we have deliberately limited references and have attempted to combine research with the experience of California farmers, who have been coping with slow water penetration for a long time. The format of this manual makes it simple to update subsections with new research as it becomes available.

"Water Penetration Problems in Irrigated Soils" was chosen as the 1986-91 mission of the Kearney Foundation of Soil Science, partially in response to a technical report prepared in January 1984 by the LAWR-Cooperative Extension Joint Infiltration Committee, co-chaired by M. J. Singer and J. D. Oster. This report indicated that about one-fifth of the irrigated cropland in California suffers from slow water infiltration and permeability, causing annual losses of $20 per acre for irrigated pastures to $1,200 per acre for orchards. Both the 1984 report and the 1985 prospectus for the 1986-91 mission indicated that problems of slow water penetration may be attributed to many factors and conditions, making correct diagnosis difficult. Many of the current ameliorative practices provide only temporary solutions.

Slow water penetration is a complex problem of major importance to California's $18 billion agricultural industry. The Kearney Foundation chose to tackle this problem in order to fill gaps in research knowledge, develop improved diagnostic methods, and explore innovative management options.

This handbook outlines preventive measures, diagnoses of problems, and management solutions. Each section deals with soil, water, and plant aspects of slow water penetration. Although this results in repetition, it reflects how a farmer considers various management options and their interactions within a production system. The flowcharts aid the handbook user in approaching specific problems systematically. The index provides another method to locate information in the manual, and the resource directory provides a list of experts on different aspects of water penetration problems.

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1.0 Introduction and Start-up Flow Charts

This manual addresses the California grower's inability to recharge the soil water content through normal irrigation operations. If during normal irrigation not enough water enters the soil to meet crop needs, you have a slow water penetration problem. We use the words water penetration to mean both water entry into soil and water movement through it.

Symptoms of slow water penetration include:

- Dry soil after long periods of irrigation.
- Stunted plant growth due to the lack of water.
- Irrigation time that is so long that it prevents or interferes with other cultural operations.
- Crop suffering from poor soil aeration and increased problems with root diseases.

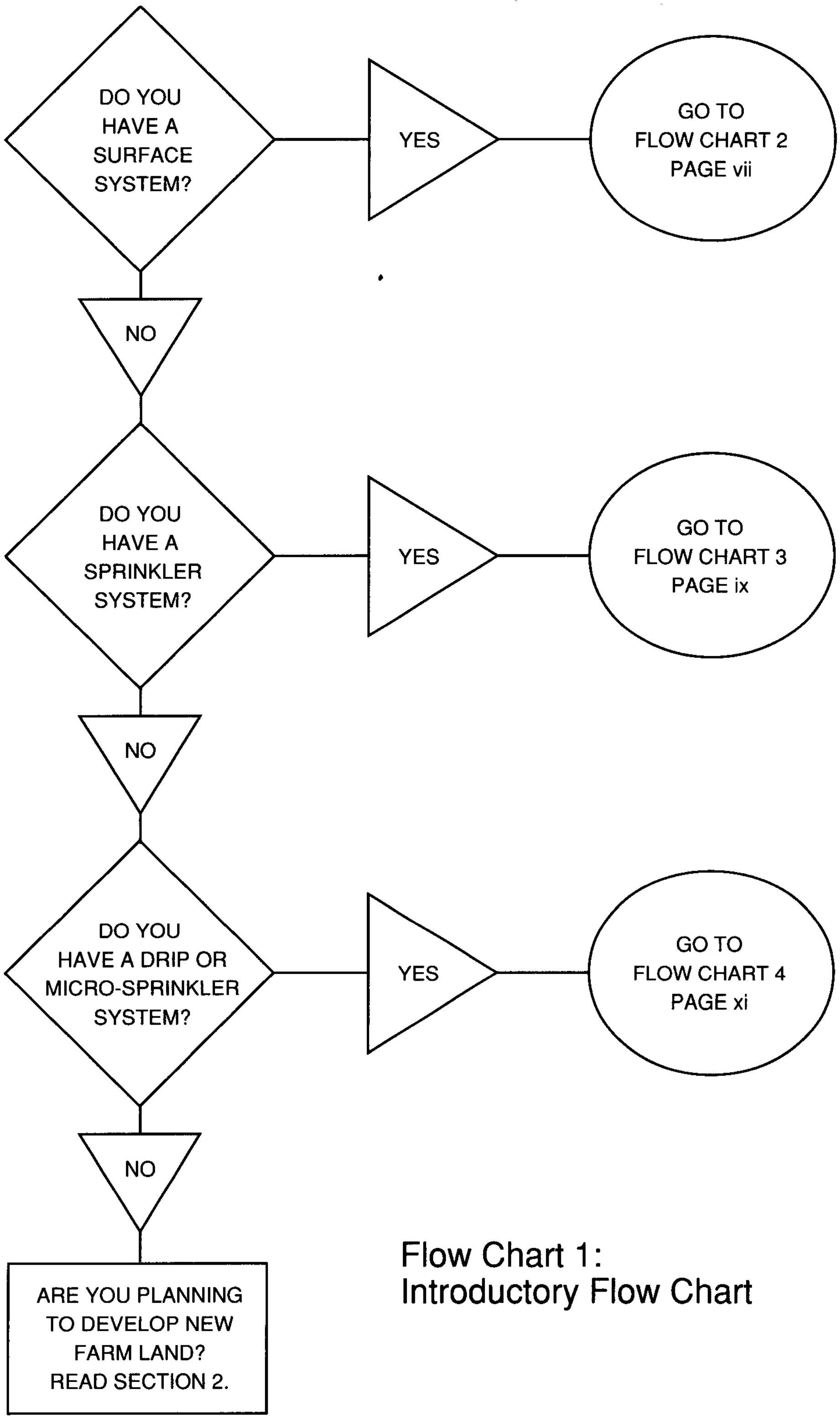
This manual is too long! We admit it. But you don't have to read every word to use it to solve your problem. In fact, you need only read through Section 2, "Prevention," and whatever parts of the last two sections that apply to your particular problem.

We have organized the manual into three sections. The most important section is Section 2, "Prevention." It is designed to help you prevent or cope with water penetration problems. Section 3, "Diagnosis," lists ways to determine what your problem might be. Section 4, "Solutions," lists solutions to various problems that cause slow water penetration.

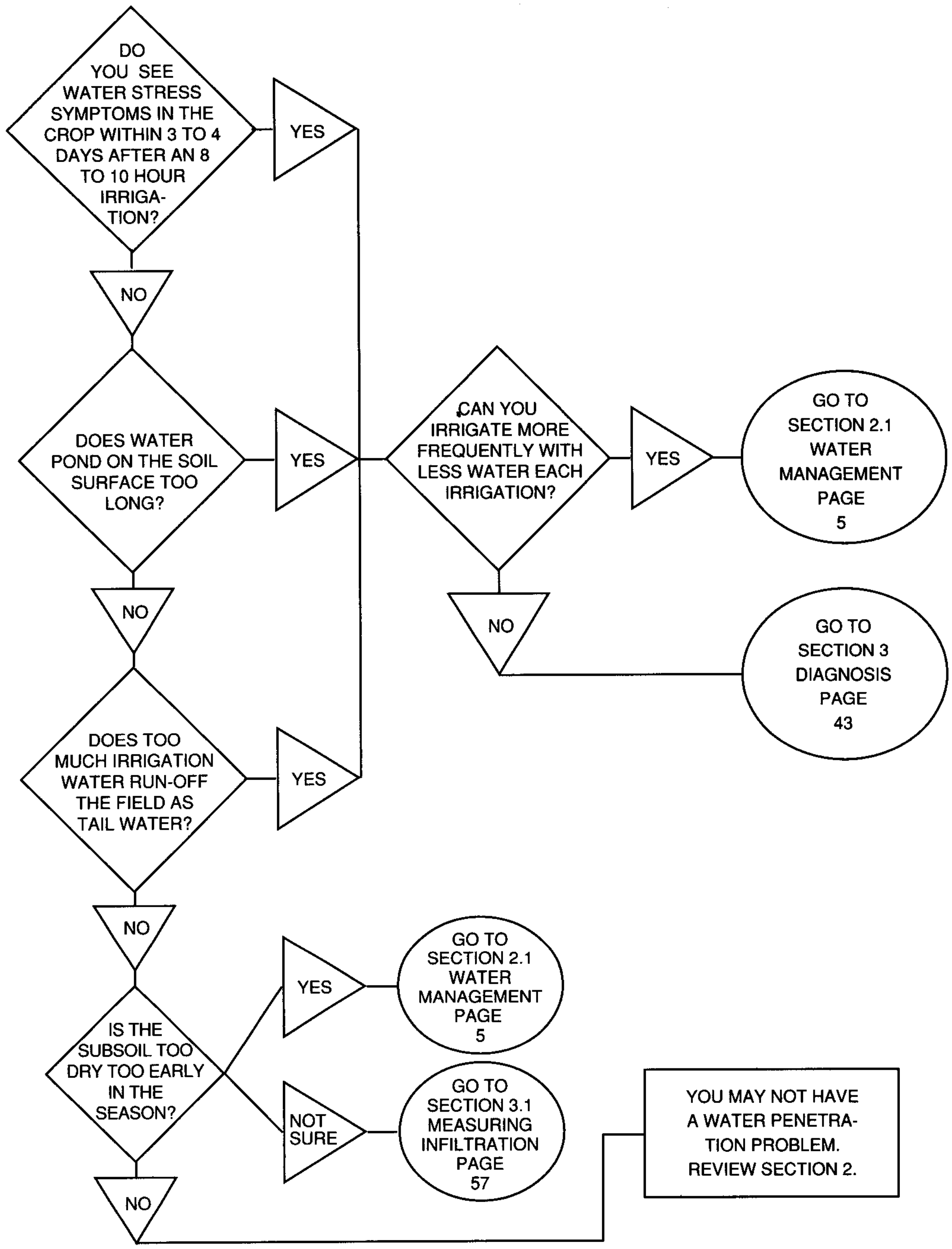
To help you use the manual efficiently, we have included flow charts. As you answer key questions, these flow charts will direct you to short sections that will help you diagnose and solve your particular problem.

For a fast start this introduction uses two flow charts. The first asks what type of irrigation system are you using. The second chart asks what symptoms of slow water penetration are evident. The symptoms are described according to soil, water, and plant characteristics that are associated with different irrigation systems. Using these two flow charts is the quickest way to begin using the last two sections of the manual.

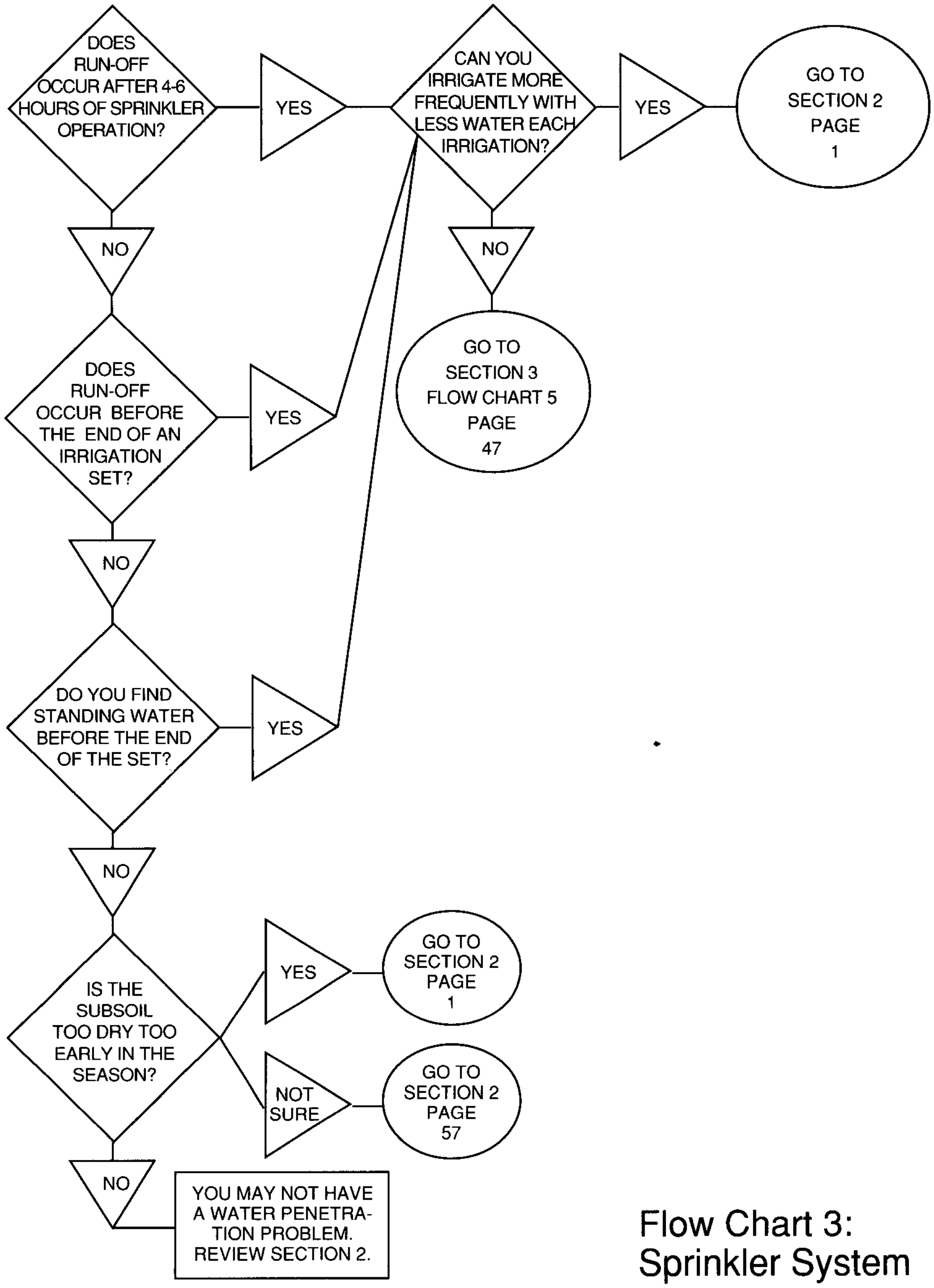
If you do not find the solution to your problem after using sections 3 and 4, read sections 2.1 through 2.4. These subsections describe ways to cope with water penetration problems. You can probably live with slow water penetration and grow a successful crop.



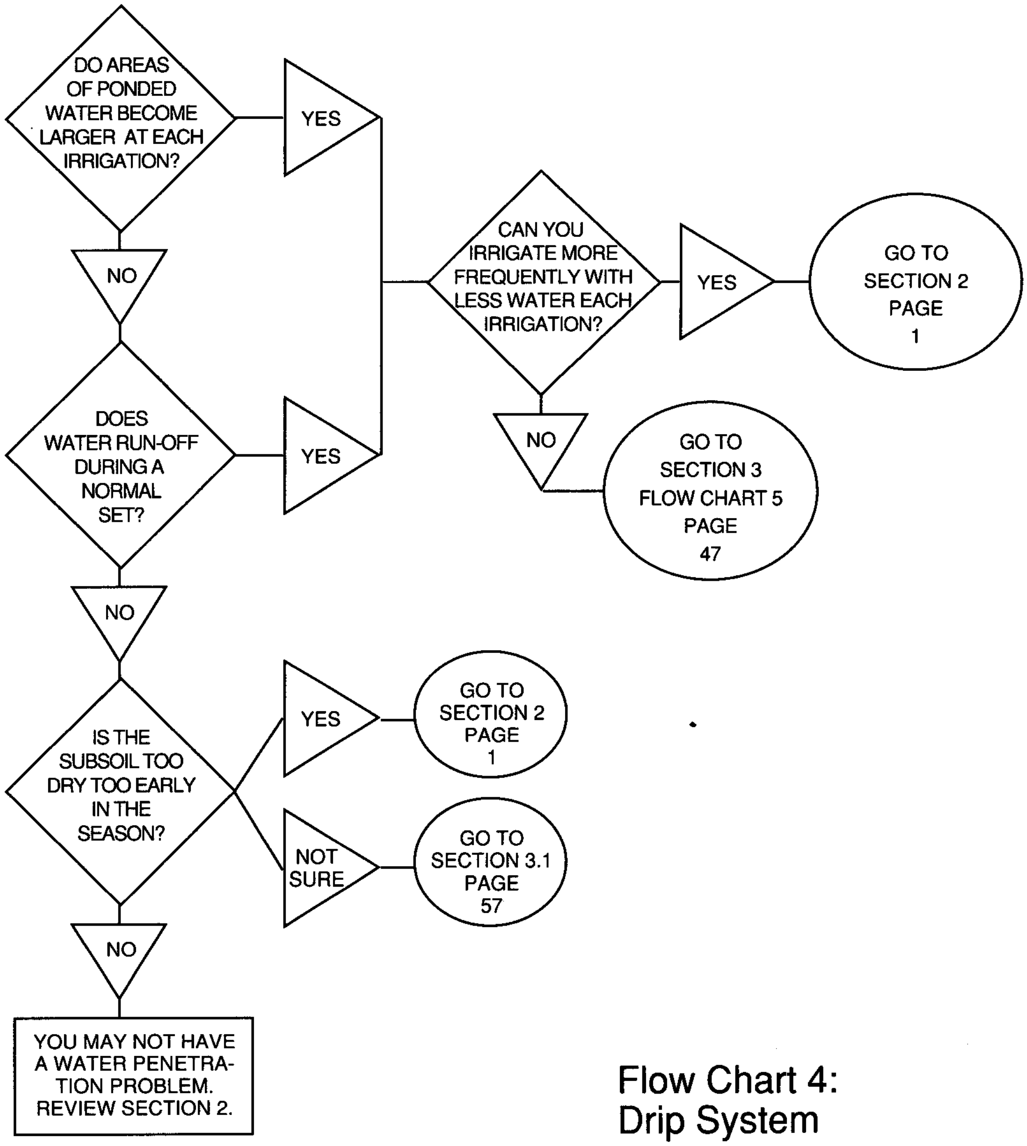
Flow Chart 1:
Introductory Flow Chart



Flow Chart 2:
Surface System



Flow Chart 3:
Sprinkler System



Flow Chart 4:
Drip System

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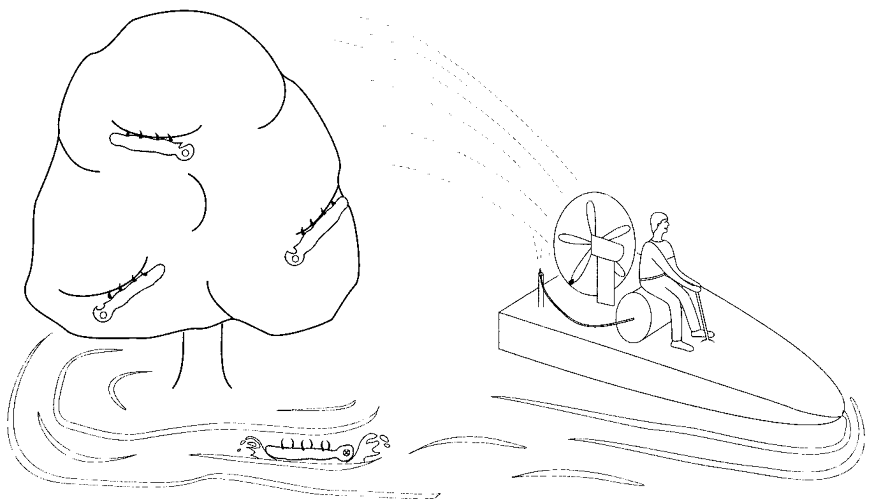
2.0 Introduction

Slow water penetration problems usually result in the inability to supply the crop with enough water. Common symptoms include dry soil near the soil surface after long periods of ponding, poor soil aeration, increased root disease, excessive wilting during July and August, and reduced crop yield. Slow water penetration can also result in increased soil salinity.



An inability to drive through the orchard to apply pesticides is another problem resulting from poor water penetration.

Before considering expensive and time-consuming solutions to slow water penetration, farmers should make sure that the problem cannot be alleviated by improved irrigation management. Improved management means better irrigation scheduling to apply enough water at the right time to meet the crop needs. Irrigation needs to replace water that has been lost from the root zone due to crop use, evaporation from the soil surface, and movement through the root zone. It also must maintain enough water in the soil to prevent soil dryness and excess salinity from reducing plant performance. Without any stored water from rainfall or previous irrigation, each irrigation needs to supply enough water to sustain the crop until the next irrigation. To be effective, this added water needs to penetrate or infiltrate into the soil.

To prevent water infiltration problems or simply to cope with them, changing irrigation practices is the first consideration. Tillage before each irrigation and the use of soil and water amendments are the next alternatives to consider. For orchards, changing vegetation management can be an effective alternative. Other more expensive alternatives include changing irrigation systems, changing crops, or trying to change the soil by slip plowing or deep ripping. Slip plowing or deep ripping, however, is effective **only** if the soil contains claypan, cemented hardpan, or layers with different textures.

Prevention of water penetration problems requires knowing how much water is needed by the crop and how much water infiltrates into the soil. **"WATER MANAGEMENT,"** the first subsection, gives examples of how such knowledge is used. These examples are taken from actual situations encountered by U. C. Farm Advisors and show step-by-step how to determine whether improper irrigation design and mismanagement are contributing to water penetration problems. However, no one evaluation technique is capable of diagnosing all possible situations. There are too many variations in irrigation systems, farm management techniques, crop constraints, and field conditions. Thus, the examples merely identify the information required to evaluate a specific irrigation system and provide guidelines on how to use the information.

2.1 Water Management

This section shows how to evaluate existing irrigation practices and to determine if irrigation scheduling needs to be changed. Two questions must be answered:

- How much water does the crop need?
- How much water infiltrates and is available for the crop?

Answering these questions requires evaluation of crop water needs and water supply, water infiltration characteristics of the soil, and water quality. With this information, management steps can be recommended to prevent or to 'live with' slow water penetration problems.

2.1.1 CROP WATER NEEDS

First and foremost, you must know the crop water needs on at least a monthly basis. A weekly basis is preferable. In determining crop water requirements, you must consider climate, crop cover, crop maturity, and any other factor that might affect the crop's water needs. For example, a mature orchard has a higher water requirement than a young orchard. Also the water requirement for any crop increases as its canopy covers more ground surface.

One way to determine crop water requirements is to look up the crop evapotranspiration data (ETc) in one of the available publications. Table 2.1 gives the crop water requirements for a variety of crops in south central San Joaquin Valley. If your crop is not listed or if your farm is not located in this region of California, UC Irrigation Scheduling Publication 21454 (Goldhamer and Snyder, 1989) is one source of additional information. Other sources include California Department of Water Resources (1986), Doorenbos and Pruitt (1977), and the California Irrigation Management Information System (CIMIS), operated by the California Department of Water Resources, DWR Office of Water Conservation, P.O. Box 388, Sacramento, CA 94230-0001. This office can provide references for water use from 96 meteorological data collection stations located throughout California.

Another way to assess adequate irrigation is to measure soil water content with instruments such as tensiometers, soil moisture blocks, and neutron probes, or by appearance and feel of the soil. Judging water content by soil appearance and feel requires a shovel and an auger, essential tools for monitoring irrigation.

Making decisions based on estimated crop needs and on soil measurements is the best approach. The more information available, the better the farmer can manage irrigation.

Table 2.1. Crop water use in South Central San Joaquin Valley conditions.

	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	SUM
PERMANENT CROPS	inches per month												inches
Almonds	—	—	—	1.6	3.1	5..1	6.6	7.9	6.8	5.0	2.8	0.6	39.5
Citrus	—	0.6	1.0	2.1	3.2	4.3	5.0	5.5	4.7	3.5	2.2	0.9	33.0
Grapes, [a] raisin/wine	—	—	—	—	0.8	3.2	4.0	4.4	3.9	2.9	—	—	19.2
Grapes, [b] table	—	—	—	—	0.8	3.2	4.9	6.3	5.6	4.2	—	—	25.0
Olives	—	—	—	—	3.0	4.7	6.1	6.7	5.8	4.3	2.7	—	33.3
Pistachios	—	—	—	—	1.3	5.3	8.7	10.2	8.5	4.9	2.1	0.3	41.3
Stone Fruit	—	—	—	1.8	3.3	5.2	6.9	7.6	6.5	4.7	2.5	—	38.5
Walnuts	—	—	—	0.3	3.0	5.8	7.4	9.4	8.1	5.4	2.3	0.3	42.0
AGRONOMIC CROPS													
Alfalfa	—	1.0	1.5	3.2	4.6	6.3	7.3	7.6	6.4	4.8	3.2	1.4	47.3
Barley	0.4	0.7	1.6	4.1	5.8	4.6	—	—	—	—	—	—	17.2
Corn planted 4/15	—	—	—	—	0.6	2.5	6.9	9.3	6.9	1.8	—	—	28.0
Corn planted 5/15	—	—	—	—	—	0.7	3.3	8.5	7.9	4.1	—	—	24.5
Cotton	—	—	—	—	0.7	1.7	6.9	9.4	7.7	2.7	0.2	—	29.3
Dry Beans planted 5/1	—	—	—	—	—	2.5	8.8	9.5	2.2	—	—	—	23.0
Lettuce planted 9/1	0.4	—	—	—	—	—	—	—	—	1.1	2.2	1.4	5.1
Lettuce planted 11/1	0.4	0.7	1.1	1.4	—	—	—	—	—	—	—	0.4	4.0
Lettuce planted 1/1	—	0.3	0.8	2.6	1.8	—	—	—	—	—	—	—	5.5
Onions planted 9/15	0.8	1.2	1.7	3.7	5.2	5.6	—	—	—	0.4	1.0	0.9	20.3
Onions planted 11/15	0.3	0.9	1.7	3.8	5.4	7.5	8.2	6.4	—	—	—	0.2	30.4
Tomatoes planted 3/1	—	—	—	0.8	1.7	6.0	7.9	4.4	—	—	—	—	20.8
Tomatoes planted 4/1	—	—	—	—	1.2	3.8	8.2	7.8	0.9	—	—	—	21.9
Tomatoes planted 8/1	—	—	—	—	—	—	—	—	2.4	4.8	3.5	1.2	11.9
Sugar Beets planted 2/1	—	—	—	0.7	1.5	3.6	7.3	8.8	9.5	7.1	—	—	38.5
Sugar Beets planted 5/1	—	—	—	—	—	—	1.9	5.3	8.9	8.1	6.0	3.8	34.0
Wheat	—	0.5	1.1	3.5	6.2	7.8	3.0	—	—	—	—	—	22.1
Pasture	—	0.8	1.5	3.3	4.9	6.6	7.8	8.2	7.2	5.3	3.4	1.4	50.4

[a] These numbers are for grapes with canopies covering 50 to 60% of the land during summer months.
[b] These numbers are for grapes with canopies covering 75% or more of the land during summer months.

2.1.2 CROP WATER SUPPLY

There are three sources of water:

1- water stored in the soil

2- rainfall

3- irrigation.

STORED WATER

Soil texture affects the amount of water that can be stored in the soil. Not all stored water is available; some is so tightly held by the soil that crops are not able to use it. Rooting depth and soil texture determine the amount of stored water available to the crop. Table 2.2 provides estimates of available water for three rooting depths, 3, 5 and 7 feet. These estimates assume: 1) soil texture doesn't vary with depth, and 2) soil water content is at field capacity throughout the soil.

Table 2.2. Available soil water estimates based on soil texture and depth.

Soil Depth	Sand	Sandy loam	Loam/Silt loam	Clay loam/ Clay
feet	inches			
3	3	4.5	6	7.5
5	5	7.5	10	12.5
7	7	10.5	14	17.5

- Begin the irrigation season with a full water profile. The more water stored, the less must be infiltrated later.

EFFECTIVE RAINFALL

Estimates of effective rainfall are important in many areas of California. When rainfall begins, it first wets vegetation and the soil surface. Any additional rainfall either infiltrates into the soil, ponds on the soil surface and evaporates, or is lost through runoff. Estimates of effective rainfall are difficult to make and subject to considerable error. Stored water from winter rainfall should be measured, not estimated.

Rainfall which occurs between October and March is a source of water that can be stored in the soil. During these months, infiltrated water is approximately equal to 0.5 times the total rainfall (California Department of Water Resources, 1989). Infiltrated rainfall which exceeds the water-holding capacity is lost due to deep percolation in the soil.

Rainfall between April and September is usually available for crop use, unless it follows a recent irrigation. During these six months, infiltrated water is approximately equal to 0.8 times the total rainfall. Snyder, in Goldhamer and Snyder (1989), pp. 28-30, describes how to make more accurate estimates of effective rainfall.

IRRIGATION METHODS

Several methods can be used to irrigate crops — surface (border and furrow), sprinkler, and drip. Each method can supply adequate water if designed and managed properly. All systems should be designed with the capacity to deliver enough water during the peak-use period (June - August) to meet crop requirement and compensate for system inefficiencies.

Irrigation methods can fall into two categories: 1) soil-controlled water intake, — surface irrigation by border or furrow — and 2) system-controlled water intake — pressurized irrigation by sprinkler or drip.

Soil-controlled water intake.

In surface methods such as border or furrow irrigation, the soil controls the water infiltration rate. Infiltration rates are initially very rapid and then decline to a steady or basic infiltration rate (Figure 2.1).

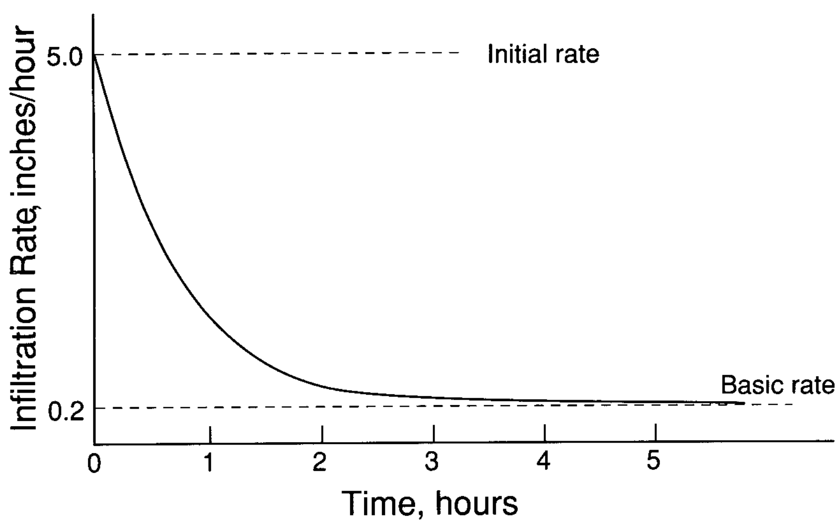


Figure 2.1. Idealized curve showing how infiltration rate changes with time.

Infiltration varies from place to place within a field. Consequently, more water must be applied than is needed by the crop to assure adequate irrigation. The time available for water infiltration, called the opportunity time, is greater at the upper end of the border, or furrow, than at the lower end. This results in more water infiltration at the upper end. Soil variability along the furrow or border is another source of infiltration variability. Application of about 20% more water than needed by the crop compensates for infiltration variability. Hanson and Wallender (1989) discuss in greater detail the impact of infiltration variability on management of surface irrigation.

System-controlled water intake.

Sprinkler and low volume methods such as drip and micro-sprinklers use sprinkler nozzles and drip emitters to control the water application rate. Water can be applied at rates about equal to the basic rate (Figure 2.1). In general, these pressurized systems apply less water per unit of time than surface systems and often require longer or more frequent applications to meet crop needs. For soils with infiltration rates less than the application rate, irrigation should be stopped when ponding or runoff begins.

2.1.3 INFILTRATION CHARACTERISTICS

The principles of water infiltration show why irrigation management is the first consideration in dealing with soils with water penetration problems. Table 2.3 describes the infiltration characteristics of a soil with a water penetration problem.

Table 2.3. Infiltration characteristics of soil with slow water penetration.

Cumulative irrigation time from onset of irrigation hour	Measured intake rate inches/hour	Cumulative infiltration from onset of wetting inches
0.25	3.00	1.10
0.50	1.00	1.60
0.75	0.50	1.80
1.00	0.20	1.90
2.00	0.10	2.10
6.00	0.05	2.40
8.00	0.02	2.60

The water infiltration rate is greatest (3.0 inches/hour) at the onset of irrigation because the water potential gradients at the wetting front are high and because water also enters the dry soil through large cracks and pores. However, after just one hour of irrigation, the infiltration rate declines to 0.2 inches/hour. As the soil becomes wet, the potential gradient becomes less steep, the cracks swell shut, and surface seals develop as large soil pores are plugged by small soil particles. As wetting continues, the infiltration rate decreases to 0.05 inches/hour. After 12 hours of irrigation, the intake rate remains nearly constant at 0.02 inches/hour. This infiltration rate is commonly referred to as the basic or steady state infiltration rate.

This soil shows the management constraints imposed by soils with low infiltration rates. Most of the water infiltration occurs during the early phases of infiltration.

In this example, nearly 74 percent (1.9 inches) of the water infiltrates during the first hour. After 8 hours, 2.6 inches have infiltrated. If a total of 4 inches is needed, an additional 70 hours would be required, assuming the intake rate does not decline further but remains constant at 0.02 inches/hour. Surface ponding that lasts 78 hours or 3.2 days is too long for crops that require good root aeration and are prone to develop root diseases.

Management options to compensate for soils with low basic intake rates depend on the type of irrigation system. With either surface or sprinkler irrigation systems that wet the entire area, increasing irrigation frequency and decreasing irrigation amount are the basic options. For drip or micro-sprinkler systems, the options include decreasing the application rate, increasing irrigation frequency, and increasing the wetted area. Another alternative is to diagnose the cause of the low infiltration characteristics (see section 3) and then to attempt to improve infiltration rates by stabilizing the soil (see section 4).

2.1.4 WATER QUALITY

Water quality, or the salinity (ECw) and sodicity (SAR) of irrigation water, influences water infiltration. It affects to what extent soil particles remain together or separate. When soil particles separate, the small particles plug the large soil pores through which most of the water flows. The higher the salt content of irrigation water the more likely soil particles will remain together and the less likely soil particles will adsorb water and become separated. The higher the sodicity, or sodium content, of irrigation water, the higher the exchangeable sodium percent (ESP) in the soil and the more likely soil particles will adsorb water and become separated.

Since both ECw and SAR of irrigation water influence aggregate stability, both must be considered when determining the likelihood that water quality can reduce water infiltration. At the soil surface the electrical conductivity of the soil water and ESP of the soil are about equal to ECw and SAR.

The following figures for Yolo loam and Hesperia sandy loam show the effects of ECw and ESP on the rate of water flow through soil. It is obvious in Figure 2.2a (Yolo loam) and Figure 2.2b (Hesperia sandy loam) that even when ESP is 3 or 0, the rate water moves through the soil decreases when ECw is less than 1.0 dS/m. All the figures show that, as ESP increases, water flow rate decreases.

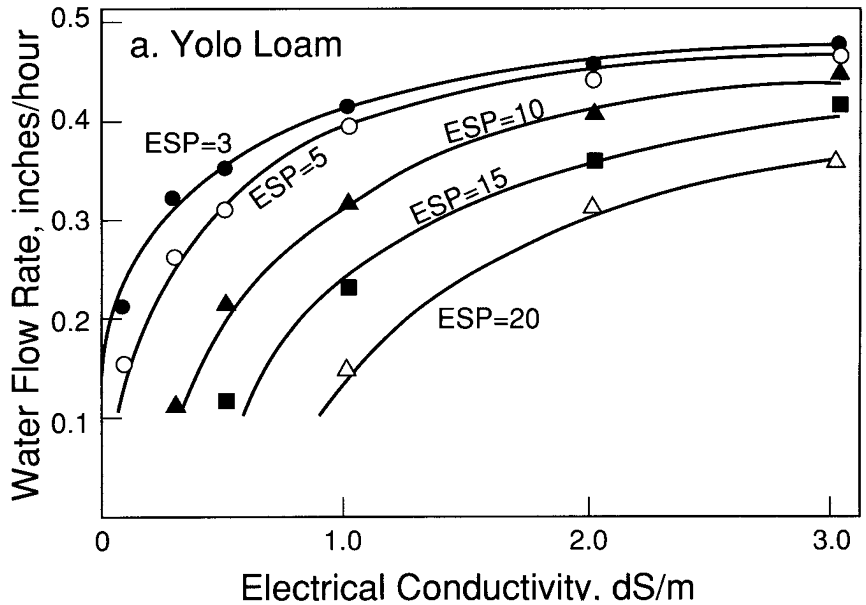


Figure 2.2a. Water flow rate through the Yolo loam soil as a function of electrical conductivity (ECw) and exchangeable sodium percentage (ESP). At any ECw, water flow rate decreases as ESP increases. At any ESP, water flow rate increases as ECw increases (Figure adapted from Henderson, 1958).

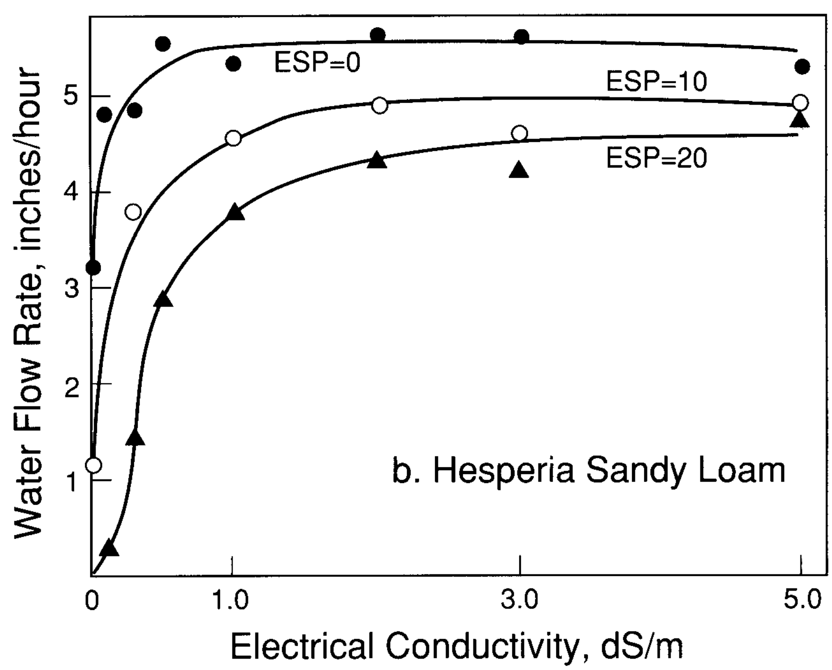


Figure 2.2b. Water flow rate through the Hesperia sandy loam. Note the flow rates are much higher than those of Yolo loam at the same ESP because of the lower clay content of the Hesperia soil (Figure adapted from Henderson, 1958).

Aggregates of soil particles on the soil surface are more sensitive to water quality effects and exchangeable sodium level than those below the surface. The surface aggregates are stirred by the flowing water during surface irrigation and by water drop impact during sprinkler application. Figure 2.3 illustrates how gypsum applied to the soil surface affects infiltration rates for sprinkler-irrigated sandy soils with varying ESP. Infiltration rates decrease rapidly with time. The higher the ESP, the more rapid the decrease and the lower the final infiltration rate. Gypsum decreases ESP and increases soil salinity, resulting in higher infiltration rates.

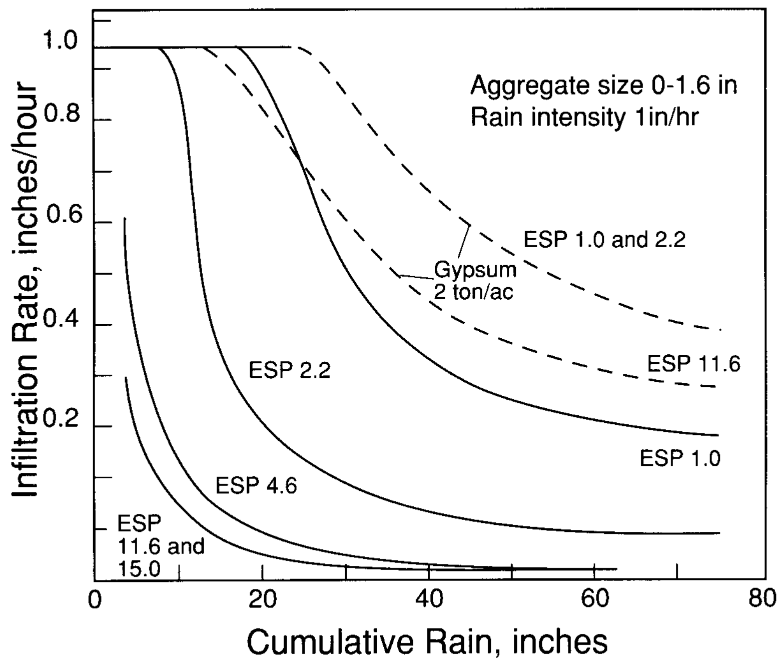


Figure 2.3. Infiltration rate of distilled water through soil aggregates with different exchangeable sodium percentage. Water is applied by a rainfall simulator at 1 inch/hour. Note the rapid decrease in infiltration rate as ESP increases from 1 to 15. Also note that 2 tons/acre gypsum helps to maintain the infiltration rate (Adapted from Kazman et al, 1983).

Calcium and magnesium are often assumed to have similar affects on infiltration and water movement through soil. This may not be the case for infiltration. Magnesium was less effective than calcium in stabilizing soil aggregates and maintaining infiltration rates against the effects of rainfall (Keren, 1991). The differences between calcium and magnesium may be greater for infiltration than for water movement through soil because of the added disruptive affects of water drop impact and flowing water. Read the literature cited by Keren (1991) if you are interested in more information about calcium and magnesium.

Shainberg and Letey (1984) concluded that significant reductions in surface infiltration rates can occur when ESP values approach zero and ECw values are less than 0.5 dS/m. Equal reductions in water flow several inches below the soil surface require ESP values exceeding 15. If gypsum is present in the soil, ESP's higher than 15 would be required.

If water quality is a problem, further information about water quality guidelines are given in section 3.3. Chemical amendments to treat problems resulting from poor water quality are discussed in section 4.1.1.

2.1.5 IRRIGATION SYSTEM EVALUATIONS

The basic questions to answer when evaluating irrigation systems are: 1) how much irrigation water is applied and 2) how much is needed. This section provides several examples of how these questions were answered by farm advisors for actual situations. The examples show step-by-step how they determined if improper irrigation design or mismanagement contributed to water penetration problems. Examples include furrow and border flood systems, sprinklers with complete surface coverage, and micro-sprinklers and drip irrigation with partial wetted area.

If you find that irrigation is being done properly, go to section 3, Diagnosis, to determine what other problems may exist.

FURROW OR BORDER FLOOD SYSTEMS

For furrow and border systems, the primary concern is how far the water penetrates during each irrigation. Each irrigation should wet the full depth of the root zone. If it does not become fully wetted, the soil may have an infiltration problem. It is, however, normal for most soils to have lower water infiltration rates in mid to late summer. Since this is also the time when water requirements are the highest, it is the time when most water penetration problems occur.

Other factors to consider are:

The time the water covers the area being irrigated affects infiltration. For most soils water should cover the area for at least 4 to 6 hours but less than 24 to 48 hours.

Excessively large heads of water often cause soil erosion and suspension of soil particles in the flowing water. Depositional crusts (section 3.6.1) form when these soil particles later settle on the soil surface.

Furrow or border checks with slopes of greater than 0.3% may cause erosion unless on-flow rates are low. This erosion can produce depositional crusts on the soil surface and reduce infiltration. Steep slopes also cause excessive runoff which reduces the amount of time available for water to infiltrate the soil.

Steep slopes also cause excessive runoff which reduces the amount of time available for water to infiltrate the soil.

In evaluating furrow and border irrigation the following information is useful:

- Water on-flow rates, obtained from pump tests or meters, or from reports from the ditch tender about canal delivery rates.
- The typical acreage irrigated in one irrigation set with these on-flow rates.
- The normal irrigation set time and any variations.
- Dates of pre-irrigation, crop irrigations, and post-harvest irrigation.
- Duration of standing water, or ponding, after irrigation.
- Amount of water stored in the root zone at the beginning of the irrigation season, based preferably on actual measurement, or else on observation and feel of soil samples (section 3.1).
- Plant stress symptoms including appearance of wilted leaves and leaf water potential measured with a pressure bomb (Grimes and Goldhamer, 1989).
- Grade or field slope.
- Depth of water penetration after irrigation.

EXAMPLE EVALUATION

For border irrigation of mature walnut trees with no cover crop, a grower wants to determine why there is poor growth and standing water after 48 hours. The following information about this system is gathered:

- The pump flow rate is 400 gallons per minute.
- The set size is about 2.1 acres per irrigation. There are 5 basins (checks) per set with each basin 30 feet wide and 600 feet long.
- The set time is 12 hours per set for all irrigations.
- The irrigation dates are May 24, June 26, July 15, August 4 and August 27.
- There have been 9.3 inches of rainfall.
- There is a 0.035% field slope.

The evaluation includes the following steps:

1- List the monthly water requirements from ETc (crop evapotranspiration) data. Find the total required for walnuts.

Month	Irrigation inches
March	0.35
April	2.50
May	5.70
June	8.65
July	9.25
August	8.00
September	5.75
October	2.45
November	0.28
Total	**42.0**

2- Calculate the average depth of water applied each irrigation by multiplying the minutes of irrigation by the pump flow rate and then dividing by the set size. This number in gallons is then divided by 27,154 (the number of gallons per acre-inch) to get the number of inches of water applied in each irrigation. Thus,

12 hour x 60 minutes/hour = 720 minutes of irrigation

400 gallons/minute x 720 minutes = 288,000 gallons water applied

288,000 gallons ÷ 2.1 acre = 137,140 gallons/acre

137,140 gallons/acre ÷ 27,154 gallons/acre-inch = 5.1 inches applied each irrigation

Application depth, D.

Estimate application depth using the following equation:

D (inches) = Q x T/(A x 450)

where:

D = depth of applied water (inches)
Q = on-flow rate (gallons per minute)
T = set times (hours)
A = acres in irrigation set
450 = conversion factor

3- Calculate the seasonal total of rainfall and irrigation water by multiplying the water per irrigation by the number of irrigations and then adding the number of inches of effectively stored rainfall. Thus,

5 irrigations of 5.1 inches each = 25.5 inches applied,

9.3 inches rainfall = 5.0 inches effectively stored in soil due to evaporative loss between rains, and

Total water available for season = 30.5 inches.

An analysis of the calculations and the information gathered by the grower indicates:

- Thirty inches of applied water only meet 70 percent of the water required for mature walnuts, assuming there are no system inefficiencies. Too little water explains the lack of growth.
- Five inches of stored rainfall will not be enough to refill the root zone of a mature walnut tree. A dormant season irrigation (in the case of too little rainfall) would ensure starting the season with enough water. The more water stored before the season, the less that must be infiltrated later.
- Comparisons of the dates and amounts of irrigation to the monthly water needs indicate irrigation frequency should be increased during the months of June, July, and August. Post-harvest irrigation is recommended too.
- An average irrigation of 5.1 inches appears to exceed the infiltration characteristics of this soil. Therefore, measures that reduce the set time with the same on-flow and set size would reduce the depth of applied water and lessen the period of standing water. Irrigation frequency must be increased to compensate for the decreased depth of applied water.
- At this site, improved irrigation management may alleviate the water penetration problem.

SPRINKLER SYSTEMS WITH COMPLETE SURFACE COVERAGE

A sprinkler system needs to apply water at a rate that does not cause runoff and yet delivers enough water to satisfy crop needs.

In setting the application rate, consider the following:

The application rate should be less than the intake rate of the soil. If the application rate ranges from 0.10 to 0.15 inches per hour and runoff occurs after 4 to 6 hours, the soil has a water penetration problem.

The system should deliver enough water to meet crop needs and to compensate for the system's inefficiency. In the Central Valley, for example, the water requirement for clean-tilled, deciduous, orchard crops is 1.2 to 2.5 inches per week from June through August. A sprinkler system with about 80% efficiency should apply from 1.5 to 3.1 inches per week to meet crop needs.

All water should infiltrate within 24 to 48 hours. Longer periods of ponding increase the potential for disease and poor aeration.

In evaluating sprinkler irrigation, the following information is useful:

- Sprinkler discharge rates at typical operating pressures (usually given in gallons per minute) and variations in nozzle sizes.
- Sprinkler spacing along a lateral and lateral spacing along the mainline.
- Number of sprinklers per lateral and number of sprinkler laterals per irrigation set.
- Irrigation set time and any variations in set time.
- Irrigation dates or typical irrigation intervals with variations carefully noted.
- Time between initiation of irrigation and the occurrence of ponding, as well as its duration after irrigation.
- Amount of water stored in the root zone at the beginning of the irrigation season, preferably based on actual measurement, or else on observation and feel of soil samples (section 3.1).
- Grade or field slope.
- Plant stress symptoms, including the appearance of wilted leaves and leaf water potential measured with a pressure bomb (Grimes and Goldhamer, 1989).
- Depth of water penetration after irrigation.

EXAMPLE EVALUATION

For sprinkler irrigation of cotton, a grower wants to know why there are symptoms of water stress in July and August and runoff after cultivation is discontinued. The following information about this system is gathered:

- Plant emergence is April 10.
- The mainline spacing is 40 feet with 40 feet sprinkler spacing along lateral lines. The laterals are 2440 feet long with 6 lines per set.
- The nozzle size is 7/64, producing 2.5 gallons per minute.
- Irrigation set times and dates are: one 48-hour pre-irrigation in February and seven 24-hour irrigations on June 3, June 24, July 8, July 20, August 1, August 13, and August 25.
- There have been 5.2 inches of rain between October and March.
- The field slope is 1.2 percent.

The evaluation includes the following steps:

1- List the monthly water requirements from ETc data and add to find the seasonal total required for cotton.

Month	Irrigation inches
April	0.4
May	0.6
June	4.2
July	9.3
August	9.0
September	3.9
October	0.9
Total	**28.5**

2- Calculate the depth of irrigation water applied by adding the pre-irrigation total to the total of crop irrigations. Thus,

Pre-irrigation total = 7.2 inches,

$$\frac{96.3 \times 2.5 \text{ gallons/minute} \times 48 \text{ hours}}{40 \text{ ft} \times 40 \text{ ft}} = 7.2 \text{ inches},$$

(96.3 is a conversion factor)

One crop irrigation = 3.6 inches, and

$$\frac{96.3 \times 2.5 \text{ gallons/minute} \times 24 \text{ hours}}{40 \text{ feet} \times 40 \text{ feet}} = 3.6 \text{ inches}.$$

> The formula to calculate applied water, D, is
>
> $$D \text{ (inches)} = 96.3 \times q \times T/(S_m \times S_l)$$
>
> where:
>
> q = average sprinkler discharge (gallons per minute)
> T = set time (hours)
> S_m = spacing along mainline (feet)
> S_l = spacing along lateral (feet)
> 96.3 = conversion factor

The sprinkler discharge can be estimated by dividing the pump capacity by the number of sprinklers, or by inserting a sprinkler into a hose and measuring the time required to fill a five-gallon container.

Total Irrigation = 32.4 inches:

7.2 inches (pre-irr.) + (7 x 3.6 inches/crop-irr.) = 32.4 inches.

3- Calculate the effective rainfall by correcting for evaporation loss. Thus,

5.2 inches total rainfall x 0.5 evaporation loss = 2.5 inches effective rainfall.

4- Calculate the total water available for the season by adding together irrigation water and rainfall. Thus,

32.4 inches irrigation + 2.5 inches rainfall = 34.9 inches.

This information indicates:

- The pre-irrigation water and rainfall should have been sufficient to infiltrate 4 to 5 feet in medium to fine-textured soils and as deep as 6 to 7 feet in coarse-textured soils. Existing pre-irrigation practices appear reasonable. Additional irrigation during the preseason would most likely drain below the root zone.

- The timing of irrigations during the season accounts for increasing water use as the crop develops. The application rates match the water use between irrigation intervals appropriately.

- If the sprinkler application system is achieving 80 percent irrigation efficiency, 34.9 inches of irrigation and rainfall should compensate for system inefficiencies and supply 27.9 inches of water for crop use.
- Since the crop shows water stress in July and August, either the sprinkler system is not achieving 80 percent irrigation efficiency (which is considered high performance for hand-move sprinklers) or runoff reduces the amount of water that infiltrates. Cultivation ends in early June, beginning what is called the "layby." In July and August, after the other layby, infiltration rates for irrigations will be less than in June and the runoff will be greater.
- Further evaluation is needed, especially to confirm whether this system's sprinklers are applying water uniformly.
- Possible remedial steps include:

  After layby, pulse irrigate. Run sprinklers for 12 hours, stop for 12 hours, and then run for another 12 hours. This should match the soil intake rate more closely and thus avoid runoff.

  Reduce the hourly application rate by modifying the system pressure or decreasing the nozzle size to 3/32. The last step would require increased set times, which may not be practical.

  If poor infiltration cannot be avoided, attempt to improve the soil's intake rate by diagnosing and correcting the soil problem. If these irrigation improvements are unsuccessful, refer to section 3, the Diagnosis section of the handbook to diagnose the soil problem and identify possible solutions.

MICRO-SPRINKLERS AND DRIP IRRIGATION WITH PARTIAL WETTED AREA

Like regular sprinklers, micro-sprinkler or drip irrigation systems should apply water at a rate that does not exceed the infiltration rate of the soil. Runoff indicates that infiltration rates have been exceeded. Emitters providing one gallon per hour should not cause runoff.

In evaluating micro-sprinklers or drip irrigation, the following information is useful:

- Micro-sprinkler or dripper emission rates based on system design specifications or actual field measurement (usually in gallons per hour).
- Number of trees or vines per acre and the number of micro-sprinklers or drippers per plant.
- Operating hours per week and operating hours per irrigation with any variations in irrigation frequency and operation time carefully noted.

- Amount of water stored in the root zone at the beginning of the irrigation season, based preferably on actual measurement, or else on visual observation and feel of soil samples (see section 3.1).
- The time between initiation of irrigation and the occurrence of ponding, and also the length of time water stands after irrigation.
- Plant stress symptoms including the appearance of wilting leaves or the leaf water potential measured with a pressure bomb.

EXAMPLE EVALUATION

For micro-sprinkler irrigation of a peach orchard, a grower wants to know why there is standing water from June through September, signs of mid-day stress, and significant tree loss from root rot. The following information about this system is gathered:

- The trees are 8 years old.
- There are 16 feet between orchard rows and 8 feet between trees within each row.
- The micro-sprinkler system with one sprinkler per tree discharges water at 7.0 gallons per hour and operates one day each week in March, April, May, September, and October and two days each week in June, July, and August.

The evaluation includes the following steps:

1- List the monthly water requirements from ETc (crop evapotranspiration) data. Add to find the seasonal total required for mature peaches.

Month	Irrigation inches
March	1.8
April	3.1
May	5.5
June	6.7
July	7.6
August	6.4
September	4.6
October	3.0
Total	**38.7**

2- Calculate the average discharge rate per hour of irrigation by calculating the number of trees or sprinklers per acre and multiplying by the sprinkler discharge rate in gallons per hour to get the number of gallons discharged per hour per acre. Dividing this number by 27,154 (the number of gallons per acre-inch) gives the discharge rate in inches per hour. Thus,

16 feet x 8 feet = 128 square feet/tree,

$$\frac{43{,}560 \text{ square feet/acre}}{128 \text{ square feet/tree}} = 340 \text{ trees/acre,}$$

340 sprinklers/acre x 7.0 gallons/hour = 2300 gallons/hour-acre,

$$\frac{2300 \text{ gallons/hour-acre}}{27{,}154 \text{ gallons/acre-inch}} = 0.088 \text{ inches/hour.}$$

Estimating Application Rate, R. The following equation can be used to estimate the low volume application rate:

$$R \text{ (inch/hour)} = 1.605 \times N \times q/(S_1 \times S_2)$$

where:

N = number of emitters per plant
q = emitter flow rate (gallons per hour)
S_1 = row spacing (feet)
S_2 = plant spacing (feet)
1.605 = conversion factor

The emitter discharge can also be estimated by dividing the pump capacity by the number of emitters or by collecting emitter outflow and measuring the time required to fill a known volume.

3- Calculate the average amount of water applied each month by multiplying the hours per month of application by the discharge rate in inches per hour. Then compare this monthly total to the monthly water requirements for peaches.

The monthly application in hours of irrigation and in inches applied follows:

Month	Time hours	Irrigation inches
April	42.0	3.7
May	73.0	6.4
June	91.0	8.0
July	103.0	9.1
August	86.0	7.5
September	61.0	5.4
October	41.0	3.6
Total	**497.0**	**45.9**

This information indicates:

- The total water applied exceeds the estimates of water use for peaches by more than 20 percent. This is appropriate if water from the micro-sprinkler system is applied with 80 percent uniformity. Properly designed and maintained, most micro-sprinkler systems will attain greater uniformity. However, the sprinklers in areas where trees are declining and water is standing the longest may be discharging too much water and causing poor root zone aeration. Checking the discharge rate of these sprinklers and maintaining the system will correct the problem.
- If the uniformity is more than 80 percent throughout the orchard, the hours of operation need to be decreased by the percentage of improvement over 80 percent. For example, if sprinkler uniformity is 90 percent, then irrigation times should be reduced by 10 percent.
- Since rainfall and stored water content at the start of the season have not been accounted for, it is possible that the initial soil water content or spring rainfall is adequate. Thus the hours of irrigation during March, April, and May can be reduced. This reduction will lessen water logging when soil temperatures are most likely to encourage disease pathogens.
- The irrigation schedule accounts for seasonal change in water use from leaf-out to dormancy. However, applying the water more frequently in the summer months (three or four times per week instead of twice) may be more suitable for the soil's infiltration rates and for keeping water from standing too long. This may be impractical because it interferes with other cultural practices.
- Since it is possible that the trees are using less water than predicted by the research guidelines, irrigation decisions should include routine measurements of soil water content along with information about crop water use.
- If the sprinklers are wetting the tree trunks, readjusting the sprinklers and using stream splitters will reduce root rot.

If these irrigation improvements are unsuccessful, refer to section 3, the Diagnosis section of the handbook to diagnose the soil problem and identify possible solutions.

SPRINKLER IRRIGATION WITH PARTIAL WETTED AREA — AN ALTERNATIVE APPROACH

The following example illustrates a method to estimate the operating hours needed to meet crop water needs. It is simple to use but provides only a rough estimate which should be checked with more precise methods. Reference evapotranspiration, ETo, is used instead of ETc. ETo is the water used by a well-watered grass crop. It is often published in local newspapers and is also available from CIMIS.

The following assumptions are made:

Corrections for irrigation system inefficiencies and crop coefficients approximately cancel each other.

Correction for partial plant cover is not needed if the crop canopy shades more than 60% of the ground at high noon.

EXAMPLE EVALUATION

For drip or micro-sprinkler irrigation of a walnut orchard, a grower wants to calculate the number of hours of operation needed to meet the crop's daily water needs.

A calculation of the hours of operation needed includes the following steps:

1- Find the individual tree or vine area in square feet by multiplying the space between tree rows by the space between trees in each row. Thus,

20 foot in-row x 25 foot between-row = 500 square feet.

2- From Table 2.4 find the daily gallons needed per tree or vine. If the water use (ETo) for a given day is 0.20 inches, the amount of water used by each tree occupying a 500 square foot area is 62 gallons.

The chart assumes at least 60% shading, at 12:00 noon, of the area by leaf cover. If the shaded area is less than 60%, multiply the gallons per day per tree or vine by the following ratio: % shaded area at 12:00 noon/60%.

Table 2.4. Daily crop water needs in gallons per tree (vine) based on plant spacing 'and reference evapotranspiration (ETo).

ETo	gallons per tree per day										
	650	600	550	500	450	400	350	300	250	200	150
inches/day	Tree or Vine Spacing, sq. ft.										
.05	20	19	17	16	14	12	11	9	8	6	5
.10	41	38	34	31	28	25	22	19	16	12	9
.15	61	56	52	46	42	38	33	28	23	19	14
.20	81	75	69	62	56	50	44	38	31	25	19
.25	102	94	86	78	70	62	55	47	39	31	23
.30	122	112	103	94	84	75	66	56	47	38	28
.35	142	131	120	109	98	87	77	66	55	44	33
.40	162	150	138	125	112	100	88	75	62	50	38
.45	183	169	155	144	126	112	98	84	70	56	42

3- Calculate the gallons per hour actually applied to each tree or vine by multiplying the discharge rate, gallons per hour, of each sprinkler by the number of sprinklers or emitters per tree or vine. Thus,

8 gallons/hour x 1 sprinkler/tree = 8 gallons/hour

4- Calculate the daily hours of operation needed to meet crop demands by dividing the daily number of gallons per tree according to the chart by the discharge rate in gallons per hour. Thus,

$$\frac{\text{62 gallons/tree}}{\text{8 gallons/hour}} = \text{7.75 hours}$$

5- Since these calculations determine only approximate amounts, more precise methods should be used if these calculations suggest that not enough water is being applied.

2.2 Tillage Management

Because improper tillage management increases surface crusting and compaction, it reduces water penetration and causes poor root growth. Proper management includes:

- Using appropriate tillage practices.
- Controlling both the time and amount of traffic.

Tillage affects surface sealing and crusting. Every time a field is cultivated the soil is pulverized into finer particles, making it more susceptible to surface crusting and compaction. Tillage methods that leave the soil surface smooth, free of plant residues, and finely divided are the most likely to cause sealing and crusting.

Compaction is a serious problem because large machinery is frequently used in preparing the ground, maintaining it weed free, adding amendments, and harvesting crops. The traffic causes dense compacted layers to form just below the tillage zone. These compacted layers are called tillage or traffic pans. Traffic pans are the reason infiltration is slower in traffic furrows than in non-traffic furrows. Also, root growth is slowed or stopped by insufficient aeration, mechanical impedance, or both.

Soil compaction results when an applied force or pressure rearranges soil particles and increases soil density. With compaction, the total volume of soil pores decreases. Moreover, while the number of small pores increases, the number of large pores decreases.

Compaction is measured most frequently by bulk density. Penetrometer resistance is also a sensitive indicator of compaction. The most obvious sign of compaction is soil that, when dug with a spade, is hard and brittle, even if the soil is moist.

Research shows that almost all tillage practices produce compaction:

- Zuzel et al (1990) have shown that soil tilled with three different implements — subsurface sweep, offset disk, and moldboard plow — had a compacted zone between 10 and 25 inches thick (Figure 2.4).

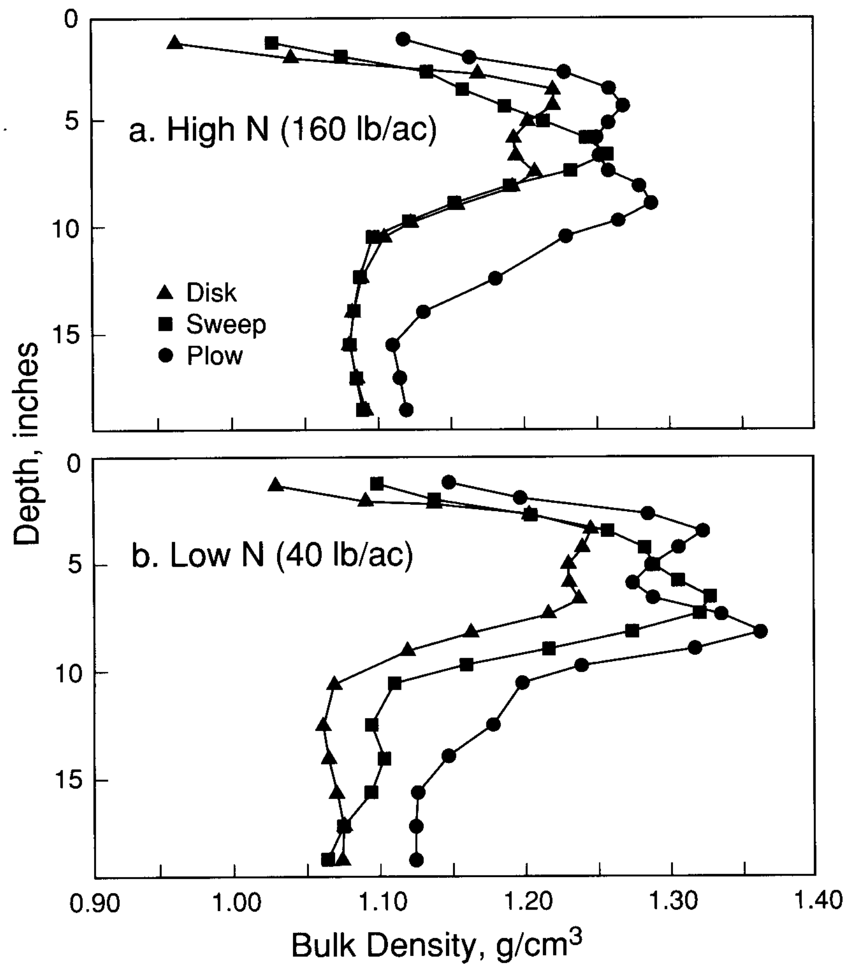


Figure 2.4. Bulk density of surface soil as a function of tillage implement and soil fertility (adapted from Zuzel et al, 1990). Note that all methods produce an increase in density. The increase is smaller for high fertility than for low fertility.

- Bauder et al (1981) measured compaction in soils cultivated with fall moldboard plow, fall chisel plow, spring disk, and no-tillage slot planting. Tillage and traffic pans were found under all tillage systems, except chisel plow.
- Waldron and Terry (1989) found that for a wet soil, surface tillage with a sliding action reduced soil infiltration rates more than tillage with a compressive action.

2.2.1 TILLAGE PRACTICES

SURFACE SEALING AND CRUSTING

Cultivation and wheel traffic increase the tendency of soils to crust. Tillage of these crusts results in only a temporary increase in water infiltration. The improvement usually lasts for just one irrigation. Some soils, however, need to be tilled in order to get a significant amount of water to enter the soil. Soils high in silt or very fine sand and low in swelling clay are the most troublesome.

Methods that break the crust but leave it rough, keeping plant residue on the surface, have the greatest chance of maintaining increased infiltration throughout an irrigation and perhaps even until the next irrigation. Various types of shallow chisels, shovel cultivators, and sweeps leave a rough and trashy surface. Application of 1 to 2 tons per acre of gypsum to the tilled surface can reduce crusting if the salinity of the irrigation water is less than 0.5 dS/m. Sodium adsorption ratios of the soil or the irrigation water greater than 5 further increase the likelihood that surface-applied gypsum would be beneficial.

TILLAGE TO BREAK UP TILLAGE OR TRAFFIC PANS

Like shallow tillage, tillage to loosen subsoil pans created by traffic is only a temporary expedient. To be effective, tillage must be deep enough. The ripping shank must extend well below the bottom of the compacted soil. This is because the major portion of the soil loosening takes place in the V-shaped pattern around the upper half of the shank.

Rip 50% deeper than the lower boundary of compaction and space shanks at 80% of the depth. Thus, if compaction extends down to 16 inches, rip to 24 inches, using shanks spaced at 19 inches.

DEEP TILLAGE OF NATURAL RESTRICTING LAYERS

Deep ripping or slip plowing is often beneficial when there are claypan, hardpan, or layers with different textures that limit deep water percolation and root growth. Before deciding to use deep tillage, however, examine the soil. If the soil is either stratified or has a hardpan within the upper 4 feet, deep tillage to a depth of 5 feet will have beneficial and usually permanent effects. Deep tillage is generally a one-time operation and is done most often before planting perennial crops such as orchards and vineyards.

Select the appropriate method for your soil condition and farm system:

- For stratified soils, use slip plows. Slip plows mix layers of different soil textures and eliminate the abrupt changes in textures across which water and roots do not move.
- For cemented hardpan, use rippers.
- Before planting perennial crops, mark the tree or vine rows in advance and rip or slip plow along these rows first. Then continue deep tillage at spacings of 5 to 6 foot intervals parallel to the plant rows. Finally, cross rip or plow only on the tree or vine row.

CONSERVATION TILLAGE

Various modified forms of land preparation have been tested in the United States under the generic term of conservation tillage. The term refers to land preparation that includes no tillage at all, minimum tillage, and reduced or altered tillage.

Conservation tillage improves water penetration because, in addition to reducing traffic, it leaves significant amounts of crop residue on the soil surface. This cover protects the soil from raindrop impact, aggregate breakdown, and crust or seal formation. The improved water penetration also prevents or delays ponding and runoff, the causes of erosion.

2.2.2 TRAFFIC CONTROL

The least costly and simplest method for reducing compaction is to modify the timing of operations that require traffic in the fields. It is best to enter the fields when the soil is comparatively dry. The soil's water content should be equal to or less than field capacity for several days. For sandy soil this level should be reached several days after irrigation, while for clay soils several weeks may be required. Waiting for dry conditions, however, may be unwise if market opportunities and crop quality will be lost because of the delay.

Every soil has a water content that will cause the most compaction. This level is influenced not only by soil texture, Table 2.5, but also by the kinds of clay minerals and amount of organic matter in the soil.

In Figure 2.5 a Proctor curve shows the relationship between water content and bulk density, a measure of compaction.

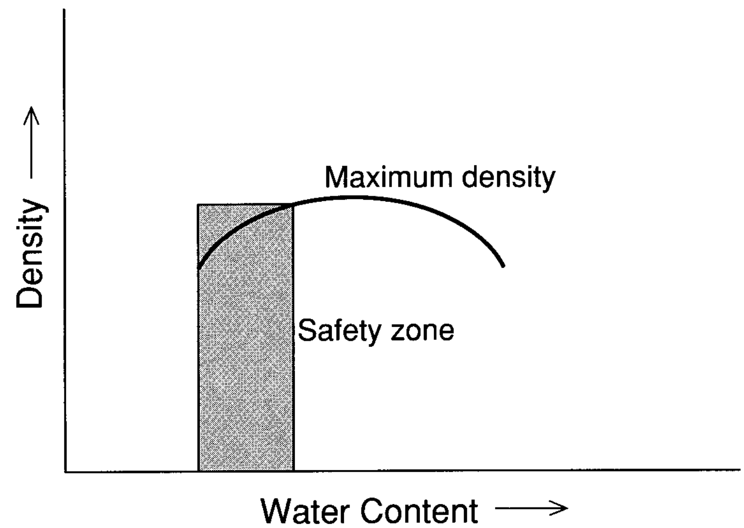


Figure 2.5. Some compaction occurs every time soil is cultivated. The extent of compaction depends on water content. This figure shows a safety zone where compaction is less likely to occur during cultivation.

Table 2.6. Optimum water content needed to reach the Proctor maximum density for several soil textures. The corresponding water contents for field capacity and permanent wilting point are also shown (Howard, 1979).

Soil texture class	Proctor maximum bulk density g/cm^3	Water content for maximum compaction %	Field capacity %	Permanent wilting point %	Organic matter %
Loamy sand	1.79	14.5	13.1	3.3	0.9
Loamy sand	1.53	19.2	16.2	6.2	4.3
Sandy loam	1.78	14.5	15.9	4.1	1.3
Sandy loam	1.46	24.2	34.3	11.2	4.7
Loam	1.76	15.4	20.0	9.1	1.6
Clay loam	1.10	45.1	45.2	27.7	7.4
Silt loam	1.27	32.1	34.2	16.3	5.6

Compaction can be minimized by reducing the size of equipment and the number of trips across the field. Use the following methods of control:

- Minimize tillage because it reduces the number of trips across the field. The benefit of fewer trips, however, will be lost if equipment size is increased.
- Try to distribute the equipment's weight over a larger area. Some helpful methods include decreasing tire inflation, increasing tire size, and increasing the number of tires and axles.
- Use fixed or permanent path vehicles to restrict wheel traffic to specific furrows or lanes, leaving the rest of the field free of traffic. Since most soil compaction is caused during the first few passes of equipment, eliminating traffic wherever possible is better than simply reducing the number of trips.

Research shows that eliminating traffic dramatically improves water penetration:

- Carter (1985), for example, found that in two years of measurement cotton fields without traffic had 21% and 32% better water penetration than cotton fields with normal traffic.
- Meek et al reported in a 1989 study that eliminating traffic in alfalfa fields led to lower bulk density and more than doubled the water infiltration rate. In a 1990 study they found that this improvement was due in part to the maintenance of the system of macropores produced by decaying alfalfa roots.

If you think compaction is a problem, see section 4 for possible additional solutions.

2.3 Vegetation Management for Tree and Vine Crops

Careful vegetation management is often the best way to prevent slow water penetration. Vegetation management refers to growing another crop between the orchard or vineyard rows. Often called cover crops, the vegetation can be weeds, planted grasses, or broadleaf annuals or perennials (Miller et al, 1989). Vegetation management is the only practical means of supplying sufficient organic matter to maintain or improve soil structure.

Annual cover crops can be grown during winter and incorporated into the soil by disking in late spring. Or, they can be mowed in the spring, leaving the plant residue on the soil surface. Perennial crops, controlled by mowing, can also be grown throughout the year. In either case, cover crops protect the soil surface from the mixing and sorting action of water flow or water drop impact. They also increase organic matter which improves soil structure. The net effect is to reduce the formation of a thin, compact soil layer at the surface which reduces infiltration rates.

Both research data and farmer experience have established that cover crops improve water infiltration. Crop productivity increases provided management adjustments are made to compensate for the increased competition for nutrients and water (Haynes, 1981). Perennial cover crops can increase water use by 20% (Prichard et al, 1989). This additional water must be supplied and infiltrate, or else yield reductions will occur. Using annual cover crops which are dead during the summer months, reduces water requirements and competition for nutrition of mature trees and vines. It also is convenient for nut crops that are harvested from the ground and for tree crops with closed canopies during the summer months.

Research shows that vegetation management increases water infiltration:

- Grimes et al (1991) measured the effects of cover crops on cumulative infiltration in a vineyard on Hanford sandy loam soil at the Kearney Agricultural Center. Cumulative infiltration was greatest in the brome grass continuous cover (CC), intermediate in the cover/herbicide-treated (CHT), and lowest in clean no-till (CNT) treatments (Figure 2.6). Differences were increased considerably the second year.
- Zuzel et al (1990) found that maintaining high fertility and leaving crop residue on the soil surface was more important for maintaining high infiltration rates than choice of tillage and reduction of compaction caused by equipment traffic (Figure 2.7).

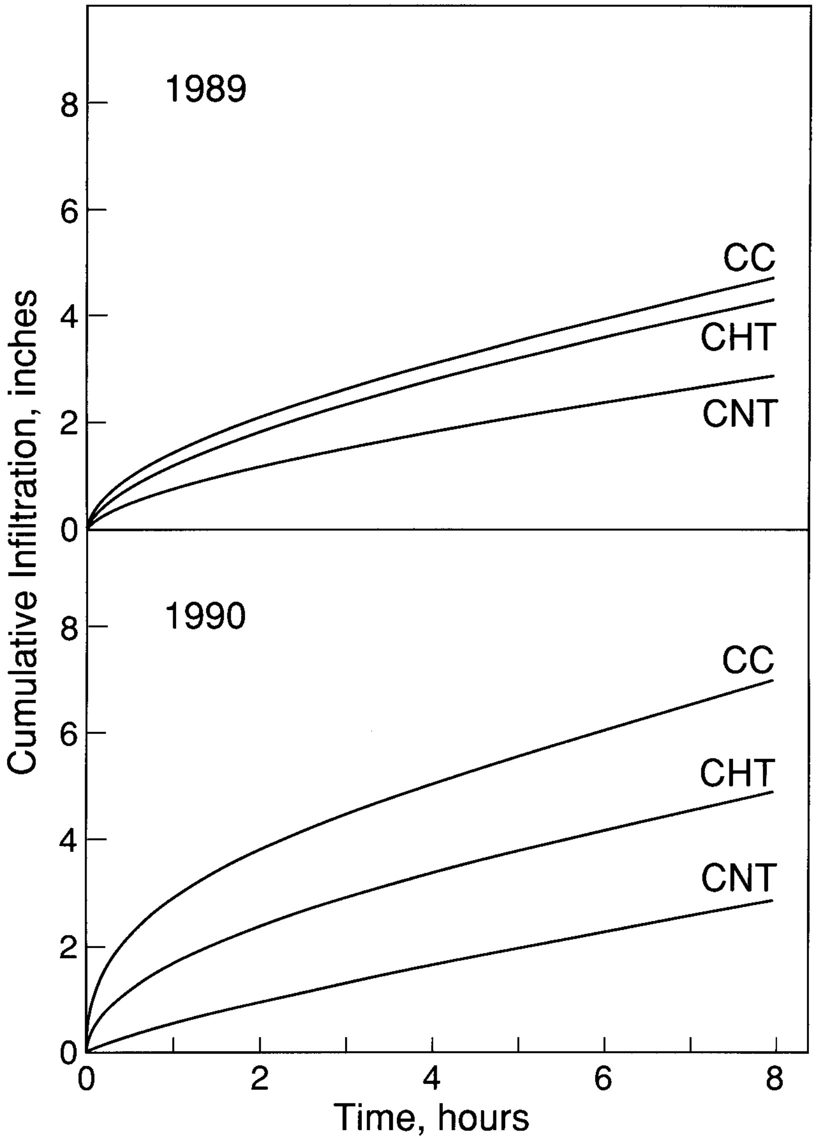


Figure 2.6. Cumulative water infiltrated into a Hanford sandy loam under three treatments, continuous cover (CC), cover + herbicide (CHT), and clean no-till treatment (CNT) (from Grimes et al, 1991). Note that in the second year the positive affect of CC on water infiltration was greater than in the first year.

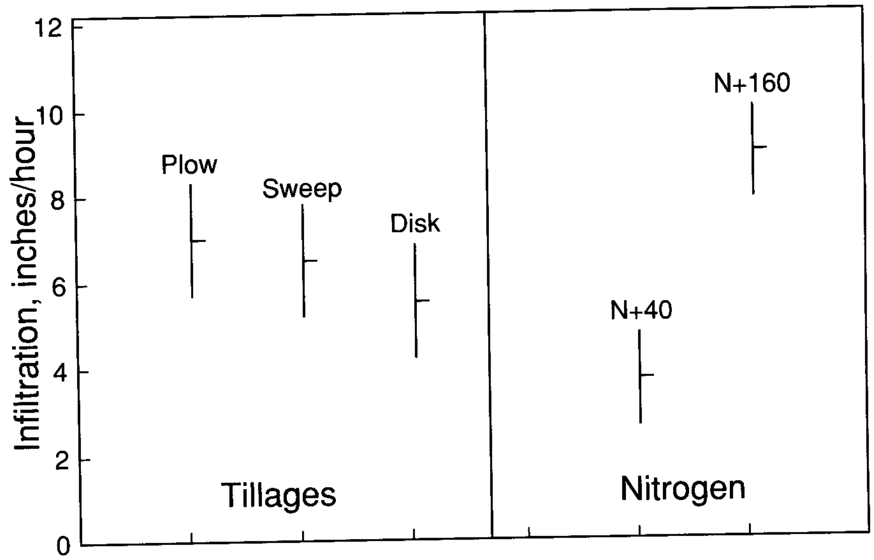


Figure 2.7. Infiltration rate as a function of tillage type and fertility (adapted from Zuzel et al, 1990). Note that the highest infiltration rate occurred under the highest fertility treatment.

2.4 Crop Selection

Although changes in water, tillage, and vegetation management can improve water infiltration, some crops may require more water than will infiltrate into the soil. Because both the amount and timing of water needs vary among crops, crop selection provides options to prevent or "live with" water infiltration problems. Through crop selection one attempts to match crop water needs with the amount of water that will infiltrate.

Crops may be changed for many reasons, such as:

1- A desire to increase profitability through conversion from annual crops to tree or vine crops.

2- The need to replace diseased tree or vine crops.

3- Attempts to improve water infiltration with the existing cropping pattern have not been profitable.

4- Farmer preference. Specialized machinery requirements and grower experience with different crops are examples of many factors which influence farmer preference.

5- Changing markets.

The key questions about water and soil when selecting crops for soils with water penetration problems are:

1- What is the crop water requirement?

2- When is the water needed?

3- How much water will infiltrate?

Section 2.1.1 provides information related to questions 1 and 2. Sections 2.1.3 and 3.2 describe infiltration characteristics and methods to measure infiltration, and Sections 2.2, 2.3, 4.1, and 4.2 describe management options to improve infiltration.

The numerous crops that can be grown in the irrigated regions of California provide too many options to cover in this manual. As a result this section focuses on general strategies and provides a few specific examples. The strategies include:

- Select annual crops which do not grow during the hottest months.
- Select tree and vine crops with the lowest water requirements during the hottest months of the year. Minimize the need for high infiltration rates.

- Select drought tolerant crops. Avoid crops that do not survive or yield well under stress from low soil water content.

- Select annual crops that provide crop residue to mix into the soil.

- Select cover crops for trees and vines to protect the soil surface and provide crop residue to mix into the soil (see sections 2.4 and 4.1.2).

The following examples illustrate some of the linkages between crops and water requirements, residue management, drought tolerance and tillage.

2.4.1 ROW OR FIELD CROPS

Some crops require more water than others. There are major differences in water needs among crops (Figure 2.8a) and when a crop is planted (Figure 2.8b).

Water requirements for the south central San Joaquin Valley (Table 2.1) vary from as little as 11.9 inches for tomatoes planted in August (Figure 2.8b) to 47.3 inches for alfalfa (Figure 2.8a).

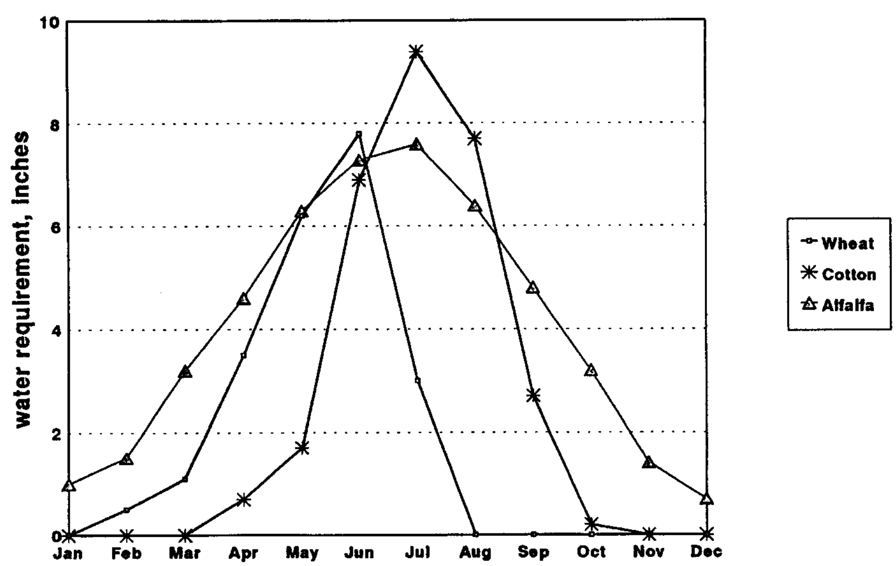


Figure 2.8a. Monthly water use by wheat, cotton, and alfalfa in the Central Valley of California.

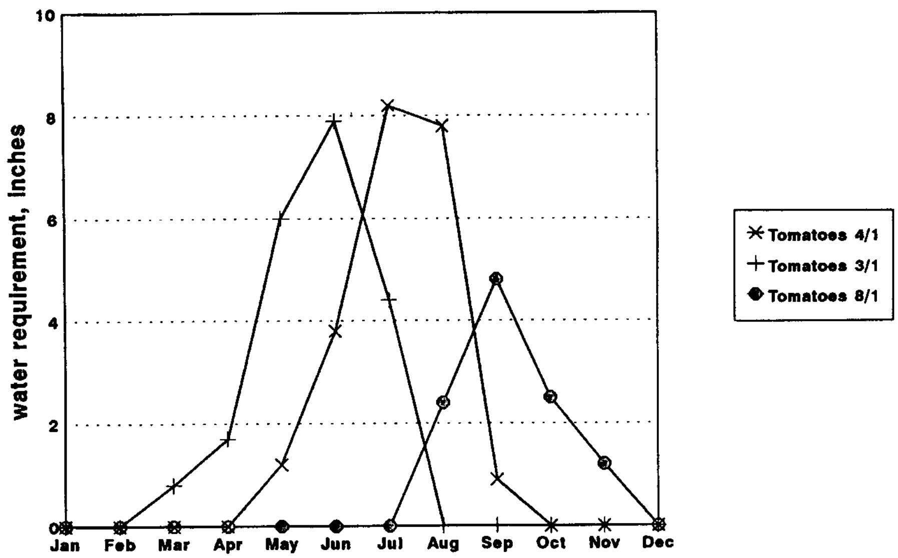


Figure 2.8b. Monthly water requirements for tomato crops planted at three different times during the year.

Water requirements for other areas of the state can be found in *Crop Water Use in California*, Bulletin 113-4, published by the State of California Department of Water Resources.

Many climate, plant, and soil factors interact with water requirement. Consult with farm advisors, SCS agronomists, consultants, and local farmers for further details and ideas. See the resource directory at the end of the manual.

Grain and vegetable crops grown in the winter may require only one or two irrigations depending on rainfall. Rainfall and sprinkler irrigation can cause soil crusting that prevents seedling establishment. Maintaining a wet soil surface with small sprinkler irrigations is one way to prevent crust development. Another alternative is to break the crust with light tillage using a rotary hoe.

Deep-rooted crops (crops like wheat, corn, alfalfa, tomatoes) draw water from a larger soil reservoir and require less frequent irrigation than shallow rooted row crops like lettuce or onions. Some crops (beans, sorghum) are sensitive to poor aeration resulting from irrigations which occur too frequently. Furrow-irrigated row crops such as tomatoes planted on wide beds (60 inches) generally require more frequent irrigations to maintain adequate soil water content than do row crops (corn, cotton) planted on narrow beds (30 - 40 inches).

Tillage of row crops provides an opportunity to increase infiltration rates until the crop is too large to use tillage equipment. Crop rotations provide opportunities to increase organic matter and thereby infiltration rates. Incorporated residues from corn grown for grain and barley for green manure improve infiltration rates for the succeeding crop. Wheat, barley, and safflower grown as grain crops also provide crop residue.

Alfalfa can tolerate drought during July and August; although yield will be reduced, it will survive (Frate et al, 1991). The following table adapted from Grattan et al, (1989) ranks the drought tolerances of grains, legumes, fruits and vegetables.

Table 2.7. Relative differences in the ability to maintain crop yield and quality under drought conditions

SENSITIVE	←			→	TOLERANT
		corn wheat		pearl millet sorghum	sunflower
		bean	soybean	peanut	cowpeas
strawberry	lettuce	tomato onion melon pea carrot broccoli pepper cauliflower	cabbage	cucumber	
	potato		sugarbeet	alfalfa	safflower

2.4.2 TREE AND VINE CROPS

Avoiding water infiltration problems should dominate the crop selection for soils with known water penetration problems. The two important variables are: mid- and late-season water requirements and drought tolerance.

WATER REQUIREMENT

Tree and vine crops need varying amounts of water throughout the year. This is illustrated in Figure 2.9 for citrus, grapes, almonds, and walnuts. In March, for example, the relative water requirements are:

grapes = walnuts < almonds < citrus.

The maximum water requirement occurs in July for these tree and vine crops, increasing in the order:

citrus < grapes < almonds < walnuts.

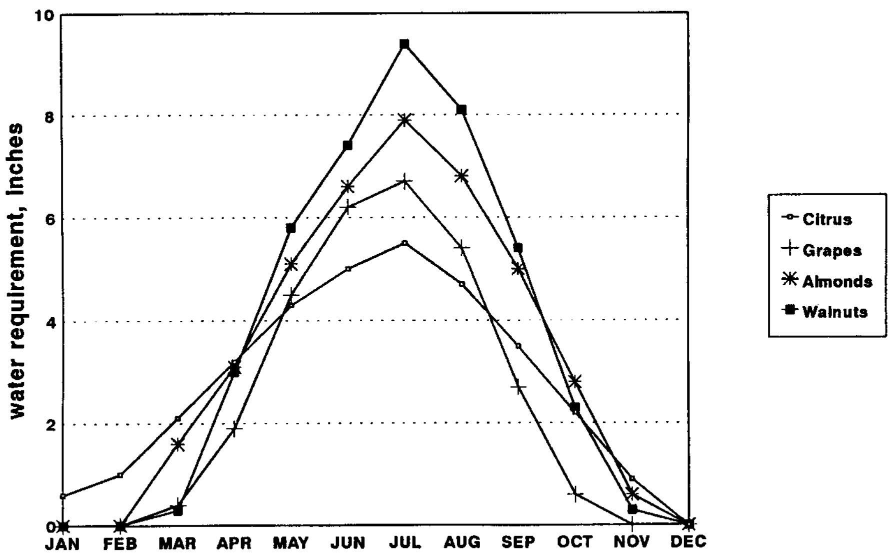


Figure 2.9. Monthly water requirements for selected permanent crops. The area under each curve represents the total annual water requirement for each crop.

Crops which leaf early (almonds) or have less seasonal or mid to late season water use (citrus and almonds) provide some opportunity to avoid water infiltration problems. According to data in Table 2.1 relative water requirements during July through September increased as follows:

citrus < raisin/wine grape < table grape < olives < almonds < stone fruit < walnut and pistachio.

Reversing the order gives the relative suitability of these crops to soils with infiltration problems. Walnuts and pistachio are least suitable; citrus and grapes are the most suitable.

DEFICIT IRRIGATION

Research on deficit irrigation, irrigation that provides less water than the maximum needs of the plant, indicates yield reductions will not occur if irrigation is managed properly. This strategy takes advantage of the observations that reduced vegetative growth due to water stress does not affect yield, or that the reproductive growth stages (bud break and fruit set) are more sensitive to water stress than vegetative growth stages.

- Deficit irrigation after harvest (about July 1) of early season peach trees did not affect fruit yields of subsequent crops (Johnson et al, 1992). They increased the time interval between irrigations from 3 to 8 weeks which resulted in a reduction in total postharvest irrigation from 30 to 15 inches.

- Research conducted in Australia on peaches (Chalmers et al, 1983) and pears (Mitchell et al, 1984) indicates deficit irrigation between fruit set and harvest reduces vegetative growth without reducing yield.
- Deficit irrigation of wine grapes at about 70% of the maximum crop requirement during mid to late season hastened fruit maturation and reduced vegetative growth without reducing fruit yield (Prichard et al, 1988) of the subsequent crop.
- Based on data obtained in a carefully controlled lysimeter study, Williams (1992) reported postharvest irrigation of Thompson table grapes at 60 to 80% of the maximum crop requirement did not affect yields of subsequent crops. The 60% applies to grapes with small canopies and the 80% applies to grapes with large canopies.
- Results from a two-year study with almonds showed that a reduction from 38 to 25 inches of irrigation did not affect yield provided leaf water potential was used to determine when to irrigate (Prichard, 1991) and provided deficit irrigation was not used before midseason (June 15).

Deficit irrigation strategies show considerable promise in reducing water needs and hence required infiltration rates for tree and vine crops during July, August, and September. However, further research is needed and special skills are required to manage the irrigation systems so that the timing, duration, and magnitude of crop stress do not result in reduced yields.

DROUGHT TOLERANCE

Grattan et al (1989) give the following ranking for relative drought tolerance in increasing order:

> cherry < peach = citrus < almond = pistachio = walnut < grape < olive

We believe the same ranking would apply for increasing tolerance to low infiltration rates particularly during vegetative growth stages.

Rootstocks affect plant tolerance to drought, salinity, and soil aeration. Drought tolerance increases with increasing root extent; the bigger the root system, the bigger the soil water reservoir. For almonds, peach-almond hybrid rootstocks are more extensive than those of peach rootstocks, and peach rootstocks are more extensive than those of prune. For cherries, Mahaleb rootstock is more extensive than Mazzard. However more extensive root systems are not necessarily more salt tolerant or more tolerant of poor aeration.

Contact farm advisors, SCS agronomists, consultants, and other farmers to gather information before selecting rootstocks. See the resource directory at the end of this manual.

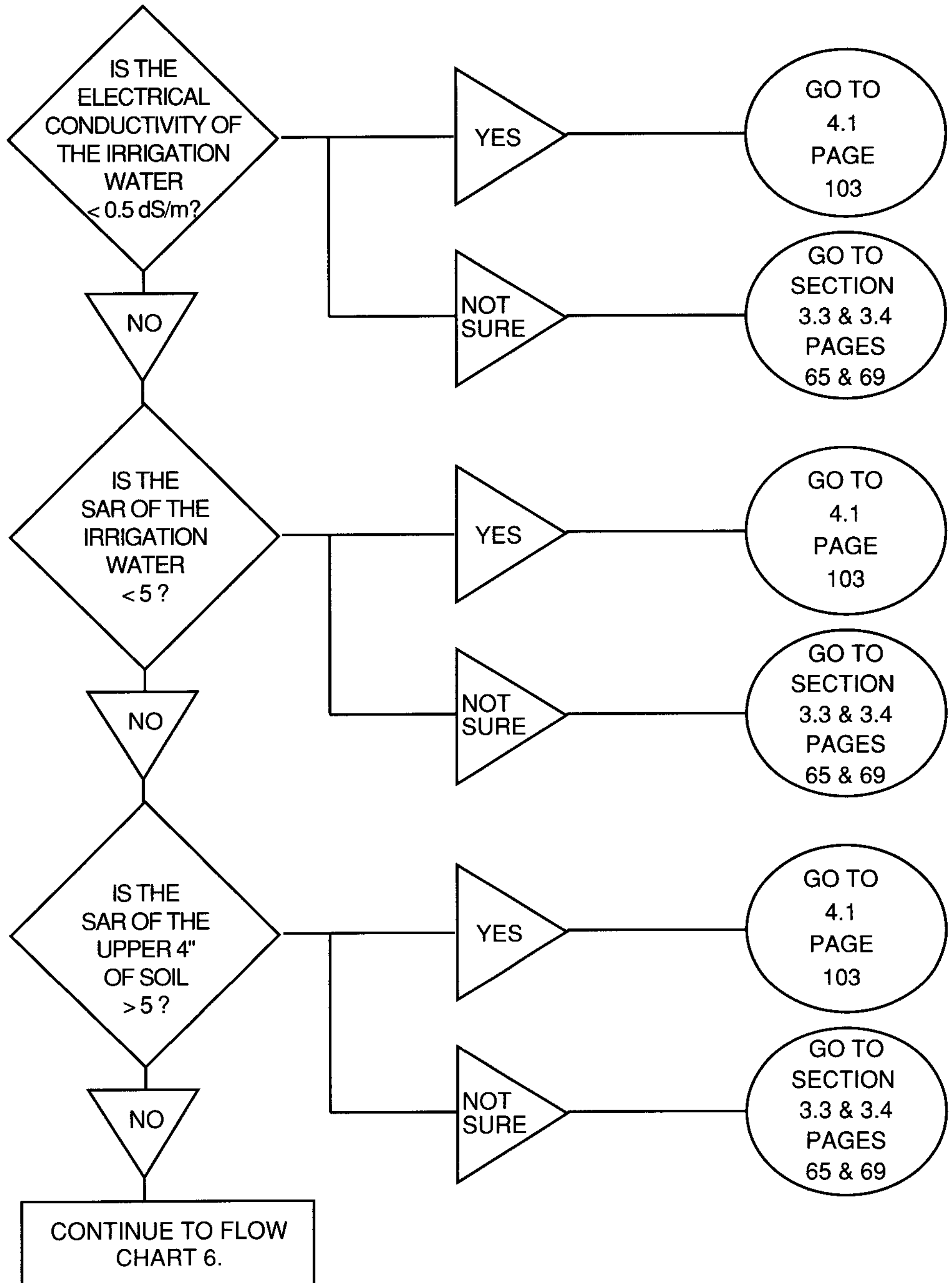
SECTION 3
DIAGNOSIS

3.0 Introduction and Flow Chart

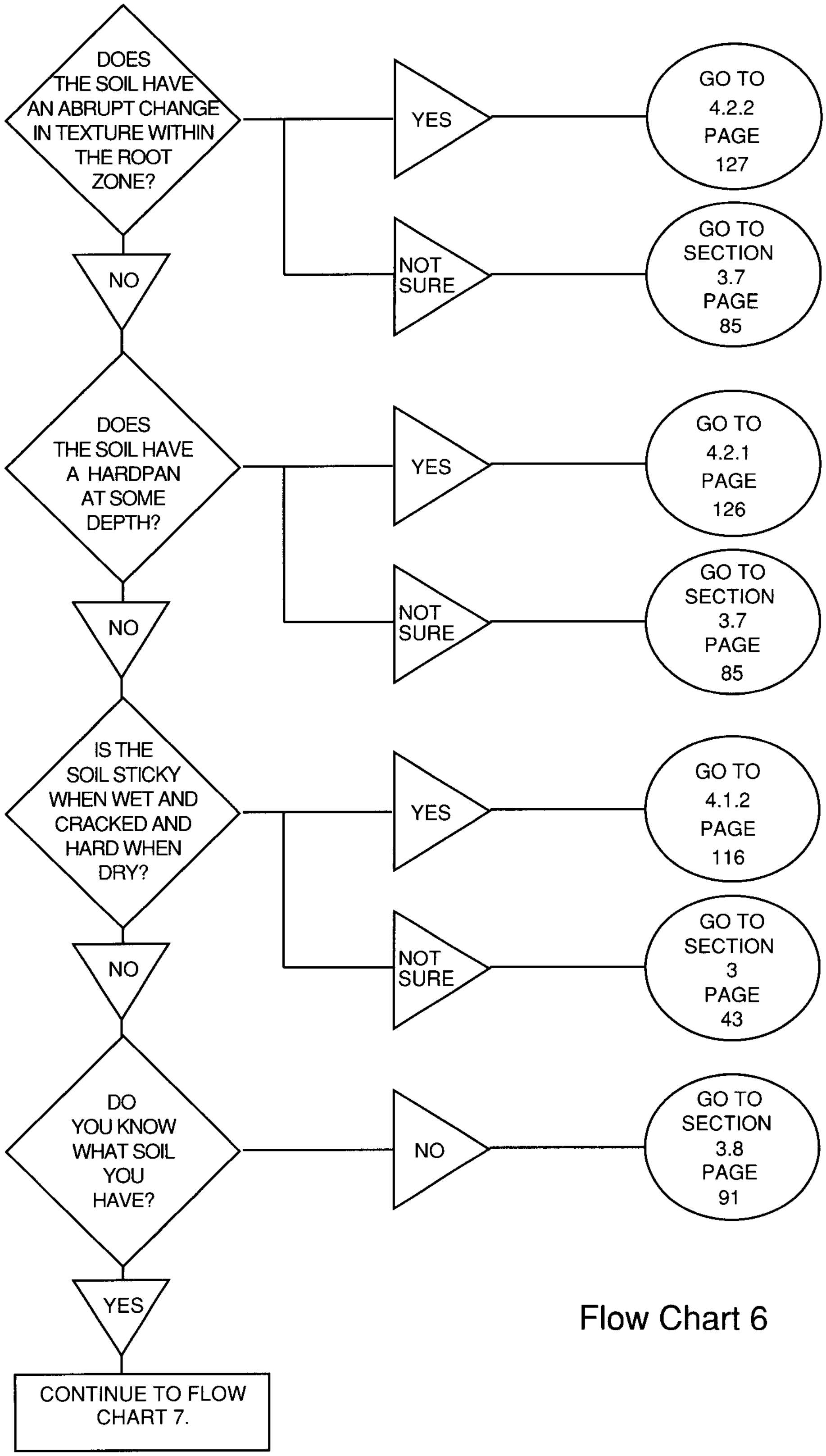
Slow water penetration has many causes including water quality, natural soil conditions, and soil and water management practices. There are simple and complex methods for diagnosing problems. Here we provide details about simple methods as well as a flow chart to guide you to the appropriate places in either the Diagnosis or Solutions sections of the manual.

The Diagnosis section is designed to allow you to find quickly the source of your water penetration problem. Only the following steps are necessary:

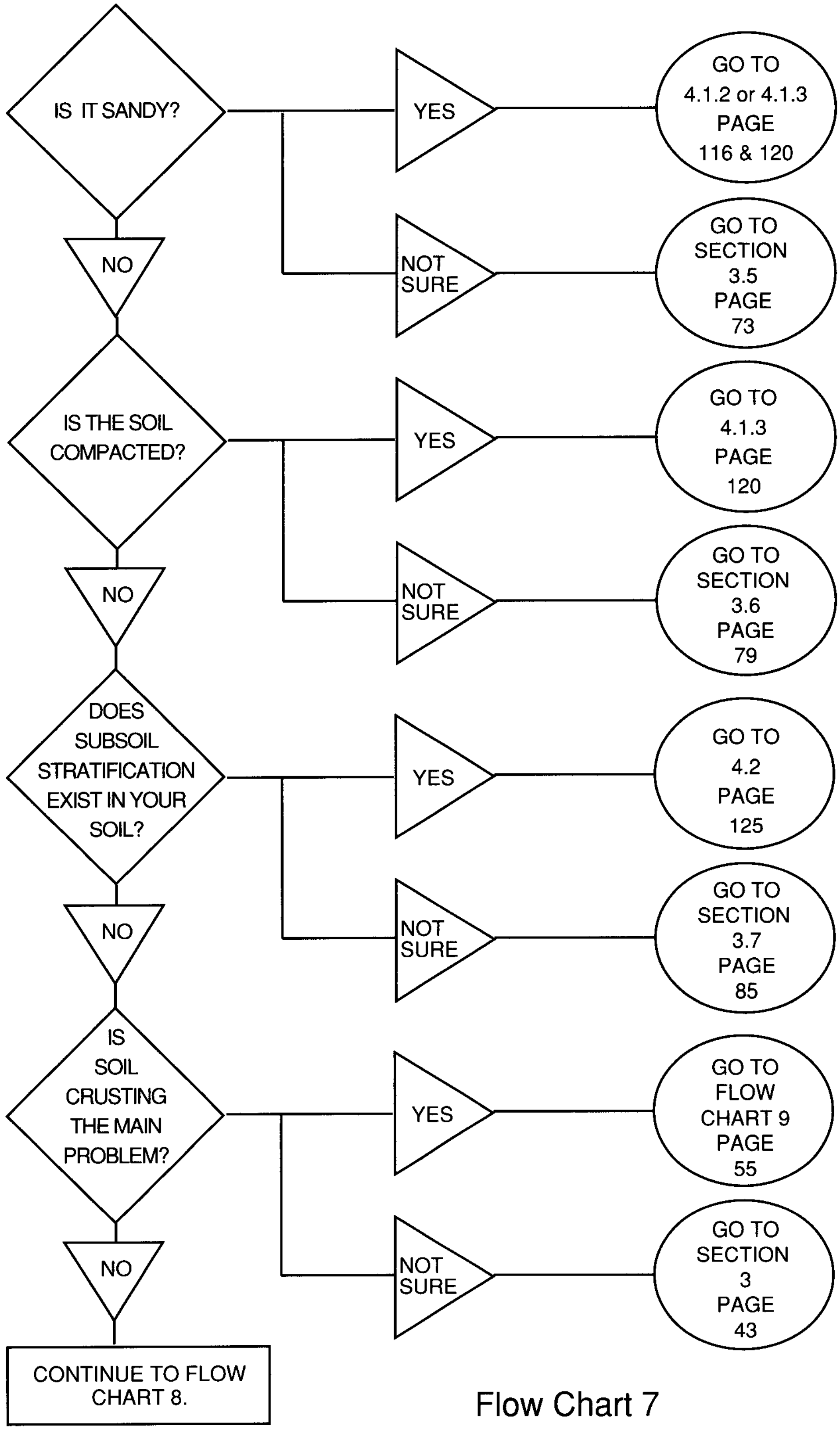
- Use the flow chart at the beginning of the diagnosis section to find the right section in either the Diagnosis or Solutions section.
- Find the right heading in the Diagnosis section if you already know what factors need to be assessed.
- Skip the Diagnosis section and look for the right place in the Solutions section if you already know the cause of your water penetration problem.
- Look in the "resources directory" at the back of the manual if the simple methods do not work or if you want additional help.


IS THE ELECTRICAL CONDUCTIVITY OF THE IRRIGATION WATER < 0.5 dS/m?
YES
GO TO 4.1 PAGE 103
NOT SURE
GO TO SECTION 3.3 & 3.4 PAGES 65 & 69
NO
IS THE SAR OF THE IRRIGATION WATER < 5 ?
YES
GO TO 4.1 PAGE 103
NOT SURE
GO TO SECTION 3.3 & 3.4 PAGES 65 & 69
NO
IS THE SAR OF THE UPPER 4" OF SOIL > 5 ?
YES
GO TO 4.1 PAGE 103
NOT SURE
GO TO SECTION 3.3 & 3.4 PAGES 65 & 69
NO
CONTINUE TO FLOW CHART 6.

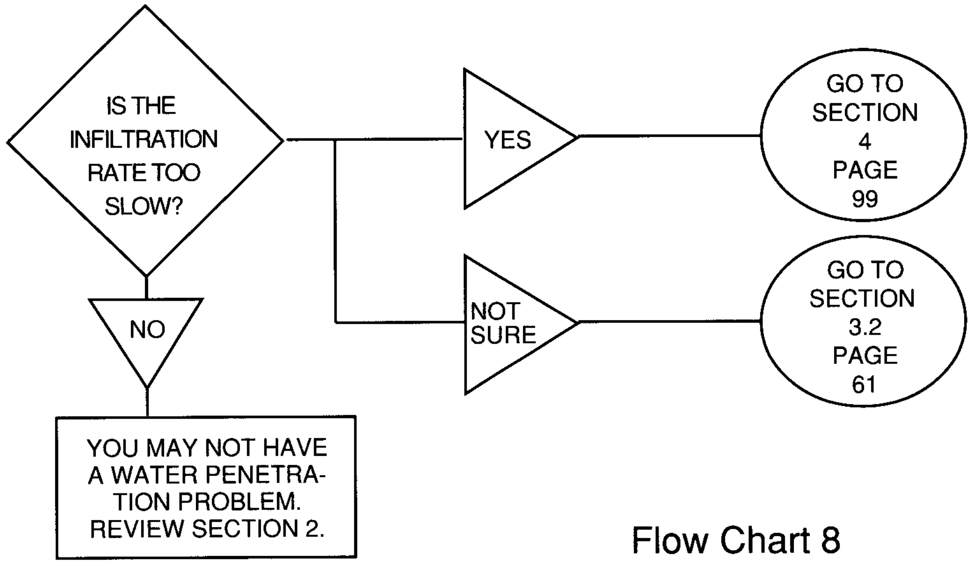
Flow Chart 5


DOES THE SOIL HAVE AN ABRUPT CHANGE IN TEXTURE WITHIN THE ROOT ZONE?
YES
GO TO 4.2.2 PAGE 127
NOT SURE
GO TO SECTION 3.7 PAGE 85
NO
DOES THE SOIL HAVE A HARDPAN AT SOME DEPTH?
YES
GO TO 4.2.1 PAGE 126
NOT SURE
GO TO SECTION 3.7 PAGE 85
NO
IS THE SOIL STICKY WHEN WET AND CRACKED AND HARD WHEN DRY?
YES
GO TO 4.1.2 PAGE 116
NOT SURE
GO TO SECTION 3 PAGE 43
NO
DO YOU KNOW WHAT SOIL YOU HAVE?
NO
GO TO SECTION 3.8 PAGE 91
YES
CONTINUE TO FLOW CHART 7.

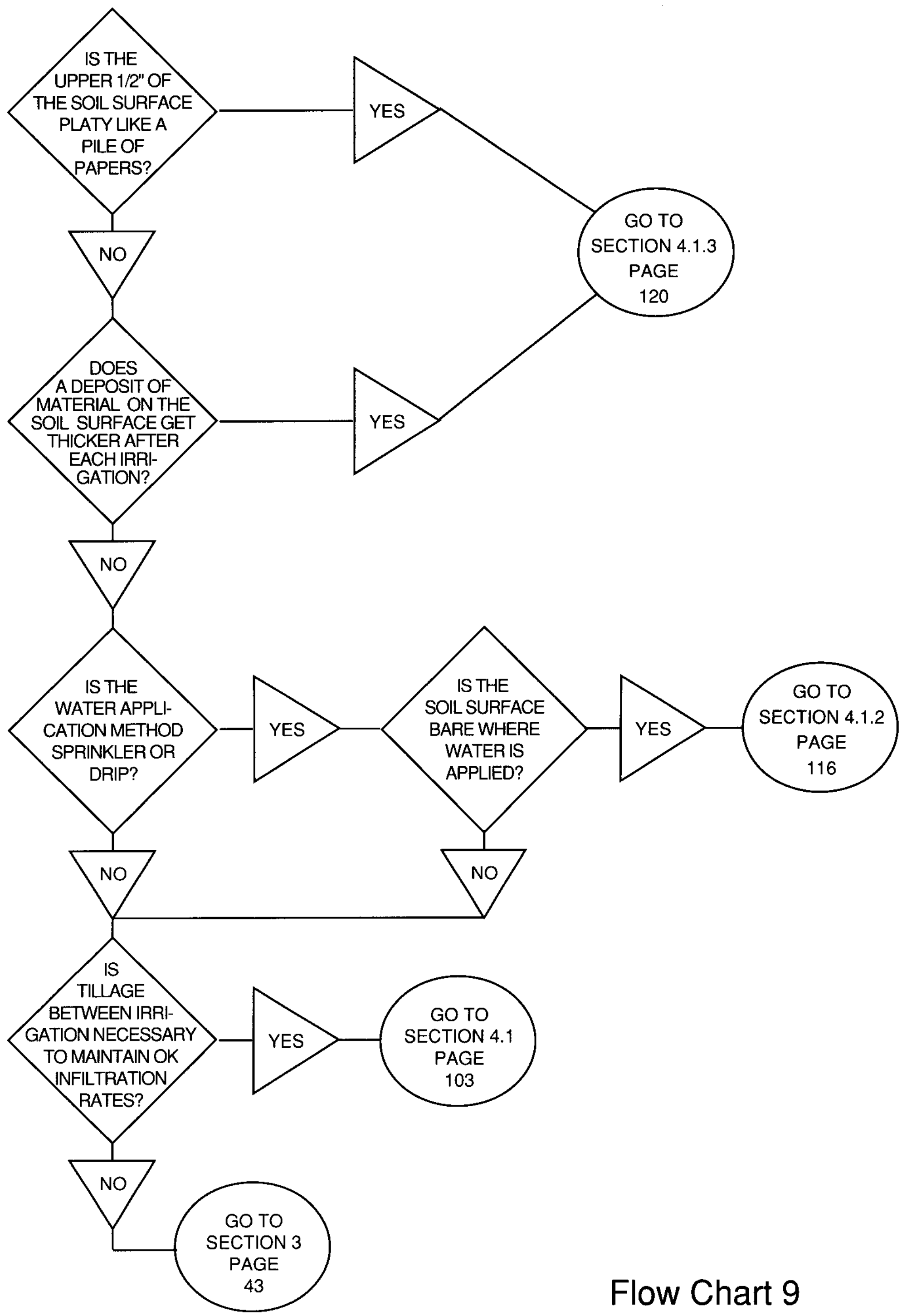
Flow Chart 6


IS IT SANDY?
YES
GO TO 4.1.2 or 4.1.3 PAGE 116 & 120
NOT SURE
GO TO SECTION 3.5 PAGE 73
NO
IS THE SOIL COMPACTED?
YES
GO TO 4.1.3 PAGE 120
NOT SURE
GO TO SECTION 3.6 PAGE 79
NO
DOES SUBSOIL STRATIFICATION EXIST IN YOUR SOIL?
YES
GO TO 4.2 PAGE 125
NOT SURE
GO TO SECTION 3.7 PAGE 85
NO
IS SOIL CRUSTING THE MAIN PROBLEM?
YES
GO TO FLOW CHART 9 PAGE 55
NOT SURE
GO TO SECTION 3 PAGE 43
NO
CONTINUE TO FLOW CHART 8.

Flow Chart 7


IS THE INFILTRATION RATE TOO SLOW?
YES
GO TO SECTION 4 PAGE 99
NOT SURE
GO TO SECTION 3.2 PAGE 61
NO
YOU MAY NOT HAVE A WATER PENETRATION PROBLEM. REVIEW SECTION 2.

Flow Chart 8


IS THE UPPER 1/2" OF THE SOIL SURFACE PLATY LIKE A PILE OF PAPERS?
YES
GO TO SECTION 4.1.3 PAGE 120
NO
DOES A DEPOSIT OF MATERIAL ON THE SOIL SURFACE GET THICKER AFTER EACH IRRI- GATION?
YES
NO
IS THE WATER APPLI- CATION METHOD SPRINKLER OR DRIP?
YES
IS THE SOIL SURFACE BARE WHERE WATER IS APPLIED?
YES
GO TO SECTION 4.1.2 PAGE 116
NO
NO
IS TILLAGE BETWEEN IRRI- GATION NECESSARY TO MAINTAIN OK INFILTRATION RATES?
YES
GO TO SECTION 4.1 PAGE 103
NO
GO TO SECTION 3 PAGE 43

Flow Chart 9

3.1 Water Content of Soil

There are three methods for determining soil water content:

1- The oldest, fastest, and simplest method is to feel the soil and judge from its feel and appearance how wet it is. The accuracy of this method depends on your experience in evaluating soil textures.

Table 3.1 is a guide to estimating water content from a handful of soil. Collect a handful of soil from the plant root zone with a soil tube or auger. Then identify the soil texture (section 3.5) and compare the feel and appearance of the soil to the description given under each of the four texture classes. Six levels of water content are described, ranging from the highest (above field capacity) to the lowest (permanent wilting point).

Each description gives the approximate soil water content in inches of water per foot of soil. To calculate how much water is available in the root zone, add the estimated values found for each depth level in the root zone. Root zone depths depend on the crop: two feet for shallow crops, such as lettuce, onions, and carrots; three to five feet for tomatoes, grapes, cotton, and grain crops; and five to seven feet for tree crops.

Table 3.1. Soil water content estimates based on feel and response of soil during handling[b].

Available water[a]	Sand	Sandy loam	Loam/Silt loam	Clay loam/Clay
Above field capacity	Free water appears when soil is bounced in hand.	Free water is released with kneading.	Free water can be squeezed out.	Puddles, free water forms on surface.
100% (field capacity)	Upon squeezing, no free water appears on soils, but wet outline of ball is left on hand. (1.0)	Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand. Does not ribbon. (1.5)	Upon squeezing, no free water on soil, but wet outline of ball is left on hand. Will ribbon about 1/2 inch. (2.0)	Upon squeezing, no free water appears on soil, but wet outline of ball is left on hand. Will ribbon about 1 inch. (2.5)
75% - 100%	Tends to stick together slightly, sometimes forms a weak ball with pressure. (0.8 to 1.0)	Forms weak ball, breaks easily. Will not stick. (1.2 to 1.5)	Forms a ball, is very pliable. Sticks readily if high in clay. (1.5 to 2.0)	Easily ribbons out between fingers, has silky feeling. (1.9 to 2.5)
50% to 75%	Appears to be dry, will not form a ball with pressure. (0.5 to 0.8)	Tends to ball with pressure but seldom holds together. (0.8 to 1.2)	Forms a ball, somewhat plastic, will sometimes stick slightly with pressure. (1.0 to 1.5)	Forms a ball, ribbons out between thumb and forefinger. (1.2 to 1.9)
25% -50%	Appears to be dry, will not form a ball with pressure. (0.2 to 0.5)	Appears to be dry, will not form a ball. (0.4 to 0.8)	Somewhat crumbly, but holds together with pressure. (0.5 to 1.0)	Somewhat pliable, will ball under pressure(0.6 to 1.2)
0 - 25% (0% is permanent wilting)	Dry, loose, single-grained, flows through fingers. (0 to 0.2)	Dry, loose, flows through fingers. (0 to 0.4)	Powdery, dry, sometimes slightly crusted, but easily broken down into powdery condition. (0 to 0.5)	Hard, baked, cracked, sometimes has loose crumbs on surface. (0 to 0.6)

Source: Adapted from Merriam (1960) and Hansen et al (1980).

[a] Available water is the difference between field capacity and permanent wilting point.

[b] Numbers in parentheses are available water contents in inches of water per foot of soil.

2- A simple, quantitative method of determining soil water content is to weigh a moist sample, dry it overnight in an oven set at 220°F, cool it, and weigh it again. The difference in weight is the weight of water. The weight of water divided by the dry weight of the sample is then multiplied by 100 to give the percentage of moisture in the sample.

For example, if a sample weighs 0.5 pounds before drying and 0.4 pounds after drying, its water content is:

$$((0.5 - 0.4)/0.4) \times 100 = 25\%$$

3- Several devices can monitor soil water status when buried in the soil. Trends in water status over time can be monitored with considerably less labor than would be required for either method 1 or 2 above. Moisture blocks, tensiometers, and neutron meters are common devices. Each requires calibration to convert the reading obtained to water content. For a detailed description of these devices, see Goldhamer and Snyder (1989).

If, immediately after irrigation, the soil is dry within the upper foot, go to Section 4.1 for possible solutions.

3.2 Measuring Infiltration

Techniques available for measuring infiltration rates are cumbersome, consume time, and require special equipment. The results also are often difficult to interpret because of the large variability of infiltration from one place to the next in an irrigated field. Variable soil types, surface soil textures, water contents, chemistries, and traffic patterns all affect water infiltration rates. The large number of ways these factors can interact makes it nearly impossible to measure infiltration rates and determine a rate representative of an irrigated field.

Although the purpose of this handbook is to diagnose, improve, and prevent infiltration problems, measurement of infiltration rates is not recommended as a diagnosis technique. Rather we recommend measuring soil water content or soil strength with a penetrometer both before and after irrigation. Both measurements are easy to do and less expensive than measuring infiltration rates. Since increasing soil water content is the objective of irrigation, measuring water content changes is a logical method to assess water penetration problems.

If measuring infiltration rates must be done, consider using one of the following methods.

3.2.1 RING INFILTROMETERS

The double-ring infiltrometer method involves two steel rings with different diameters, for example 8 and 12 inches. These rings need to be inserted with as little soil disturbance as possible. They should be inserted straight down without rocking. The insertion depth should be as shallow as possible to reduce soil disturbance, but deep enough to prevent water from escaping through cracks or holes below the cylinder (Bouwer, 1986).

A constant water level can be maintained in both cylinders with a Mariotte syphon, and the infiltration rate can be measured from the rate of decline in the water level in the Mariotte reservoir. Or the water supply can be periodically stopped, and the infiltration rate determined by measuring the time it takes for the water surface to drop a small distance, such as 1/16 of an inch. This technique can be used if the infiltrometer rings are surrounded by water as in a flooded field.

This method is inexpensive and simple, but many sites must be measured to obtain a representative measurement for an irrigated field. Bouwer (1986) states that "no hard and fast rules, however, can be given for the number of infiltrometer measurements that are necessary for a given situation" and recommends the following guidelines:

- Determine infiltration rates by soil type based on soil surveys.
- Start with a minimum number of measurements (5 for example) for each soil type, "adding more if results vary too much to get an acceptable average infiltration rate." What is acceptable becomes a judgment call, improved by experience, but subject also to time and labor constraints.

3.2.2 INFLOW-OUTFLOW METHOD

This method is best suited for measuring infiltration in furrow systems. If water storage in the furrow does not change, the rate of inflow into a furrow minus the rate of outflow at a given time equals the infiltration rate. Depending on accuracy of flow measurement and soil texture, furrow lengths required for measurement depend on soil texture, ranging from about 150 feet for coarse-textured soils to about 700 feet for fine-textured soils (Kincaid, 1986).

This method is less subject to small scale variations in infiltration rates than the ring infiltrometer method. However, the infiltration rates of traffic and non-traffic furrows will be different, and changes in soil type within an irrigated field as well as within the test section of a furrow, will also affect infiltration rates. The inflow-outflow method requires more time than the ring infiltrometer method, and analyzing the data to develop the changing infiltration relationship over time requires special skills.

3.2.3 RAINFALL SIMULATOR

This infiltrometer applies water at controlled rates ranging from 0.05 to 4.0 inches per hour in increments as small as 0.05 inches per hour. It consists of a platform about 15 feet square (5 feet x 3 feet) with hundreds of hypodermic needles mounted in rows on small-diameter pipes on the bottom side of the platform (Fig. 3.1). By means of a electrical pump and plumbing system, the pipes drip water through the needles onto the soil surface below the platform. The platform moves back and forth horizontally providing short wetting and drying cycles on the soil surface (Prichard et al, 1988).

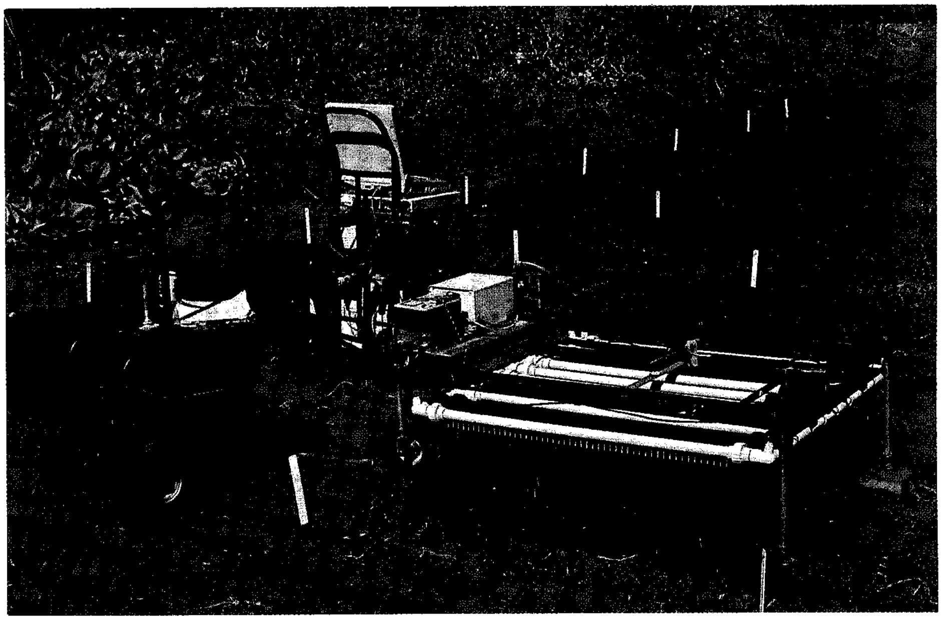


Figure 3.1. Rainfall-simulator infiltrometer used for determining soil infiltration rates. Note the water drop formers attached to the white plastic pipes. These pipes move horizontally under the green metal frame. The computer controller is located to the left rear of the unit.

The infiltration rate is measured over three or four hours. Initially, a high flow rate equal to 4.0 inches per hour is dripped onto the soil surface until ponding is observed. The time required for ponding to occur is recorded for the specific flow rate. The flow rate is decreased in increments of 0.1 to 0.2 inch per hour until the basic infiltration rate is determined. This rate is reached when it takes at least 30 minutes for ponding to occur.

The **disadvantages** of a rainfall simulator are:

- It requires special equipment, and only one or two have been made. Your Farm Advisor can make arrangements for use of a rainfall simulator, or you can request blueprints by contacting the Department of Land, Air and Water Resources at Davis. Construction, however, is expensive.
- Like a ring infiltrometer, a rain simulator measures infiltration only of small areas within a field and does not take into account the variations in infiltration rates from place to place which commonly occur.

The **advantages** of a rain simulator are:

- It simulates the effect of droplet impact on the soil surface.
- It can be used to test the effect of different water qualities on infiltration rates by changing the source of water pumped through the simulator.

If you measure infiltration and find the rates are too slow for your irrigation system, go to section 4.1 for possible solutions or go to section 2 for ways to manage your irrigation system.

3.3 Irrigation Water Quality

Irrigation water quality influences water infiltration or water penetration. It affects whether soil particles tend to adsorb water, whether they tend to remain together, or become separated by swelling. Swelling causes aggregate breakdown and dispersion of soil particles. These processes reduce water infiltration rates because swelling, aggregate breakdown, and soil particle dispersion cause the formation of dense soil crusts and reduce the size of the largest soil pores through which most of the water flows.

3.3.1 SALINITY

The higher the salinity of the irrigation water the more likely soil particles or aggregates will remain together. Salts decrease the affinity of soil particles for water and consequently their tendency to imbibe water. Aggregate stability increases with increasing salinity of the irrigation water or the water in the soil.

The index of salinity is the electrical conductivity of the irrigation water (ECw) or of a soil water extract (ECe) obtained from a saturated soil paste. (See section 3.4.1 for soil sampling instructions.)

When sampling irrigation water, follow the techniques below:

- Collect a small but representative sample of the irrigation water (4 to 8 oz, or 120 to 240 ml).
- Collect well water only after pumping for at least thirty minutes. This should be sufficient time to flush the well and to establish the water elevation which exists during most of the pumping period. This assures that the water sample represents the water in the primary, water-bearing strata.
- Reanalyze well water if ECw varies more than twenty percent for different measurements. Usually the chemical composition is stable. But well waters can change composition during an irrigation season if the water elevation in the well drops. This change occurs when water pumped from groundwater aquifers exceeds the rate of aquifer recharge.
- Collect surface water from canals flowing water.
- Use sample containers that are clean, rinsed in the water being sampled, filled completely, and sealed.
- If it is not possible to submit the samples for analysis the same day, refrigerate them to reduce changes in EC and concentrations of calcium and bicarbonate due to lime precipitation.

3.3.2 SODICITY

Sodicity is a more complicated parameter than salinity. The index for sodicity is the sodium adsorption ratio (SAR) which depends on the sodium, calcium, and magnesium content of the irrigation water. SAR is used to estimate exchangeable sodium levels in the soil. The higher the SAR of the irrigation water, the higher the exchangeable sodium levels of the soil. With increasing exchangeable sodium, the affinity of soil particles for water increases and aggregate stability decreases.

SODIUM ADSORPTION RATIO

Calculation of SAR requires measurements of the concentrations, C, of sodium, calcium, and magnesium in the water. If concentration is in meq/L, the equation is:

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

ADJUSTED SODIUM ADSORPTION RATIO

The sodium adsorption ratio of irrigation water is often adjusted to account for precipitation or dissolution of lime ($CaCO_3$). There are two methods for calculating the adjusted sodium adsorption ratio. The abbreviation for the older method is SARa. We will use the symbol SARadj (Jurinak and Suarez, 1990) for the newer preferred method, developed by Suarez (1981) and calculated according to procedures described by Ayers and Westcot (1985), pp. 62 and 63, or by Jurinak and Suarez, 1990, pp. 60 and 61. Another alternative is to use WATSUIT, a computer program which computes the chemical composition of soil water (Oster and Rhoades, 1990). The number computed by WATSUIT and labelled SUR.SAR in the computer printout equals that for SARadj.

If the SARadj is greater than SAR, calcium concentrations are projected to decrease because of lime precipitation. If the reverse is true, then calcium concentrations are projected to increase because of dissolution of lime in the soil or other soil weathering reactions which release calcium and magnesium (Suarez and Rhoades, 1982).

Only sodium adsorption ratios of irrigation water are adjusted. Sodium adsorption ratios of soil water extracts are not adjusted because this water has had an opportunity to equilibrate with soil lime and other soil minerals.

3.3.3 COMBINED EFFECT OF SALINITY AND SODICITY

Both salinity and sodicity of irrigation water influence aggregate stability and water infiltration rate. Thus, both must be assessed in diagnosing a water penetration problem and in determining whether changing the ECw or SAR of the irrigation water can be expected to reduce the water penetration.

In the top three inches of soil, the salinity and sodicity of the irrigation water and soil water are closely linked. Where poor water penetration is a problem, salinity and sodicity of the soil water are often greater than those of the irrigation water. Consequently, a good diagnosis includes an analysis of both the irrigation water and soil-water extracts obtained from surface soil samples.

The guidelines in Table 3.2 show which salinity and sodicity levels have a high probability of affecting water infiltration (Shainberg and Letey, 1984; Quirk, 1986). Keep in mind that water quality may still affect water penetration even if the salinity and sodicity of the soil water are about equal to the corresponding numbers for the irrigation water. If so, water penetration will improve by increasing the salinity and decreasing the sodicity of the irrigation water. Injecting gypsum into the irrigation water or applying gypsum to the soil surface will improve the levels of salinity and sodicity of the irrigation water. Laboratory tests using soil columns, both treated and untreated with gypsum, can also be conducted to determine if gypsum will improve water penetration (Rhoades and Loveday, 1990).

Table 3.2. Combined effect of sodium adsorption ratio and electrical conductivity of either irrigation water or soil water on the likelihood of water infiltration problems.

When sodium adsorption ratio of the irrigation water or soil water is	Potential water infiltration problem	
	UNLIKELY IF ECe or ECw IS	LIKELY IF ECe or ECw IS
0 - 3	> 0.7	< 0.3
3.1 - 6	> 1.0	< 0.4
6.1 - 12	> 2.0	< 0.5
12.1 - 20	> 3.0	< 1.0
20.1 - 40	> 5.0	< 2.0

At an SAR between 0 and 3, irrigation waters with ECw less than 0.3 dS/m are likely to cause water penetration problems whereas those with ECw greater than 0.7 dS/m are not. Similarly those with an SAR between 3.1 and 6 are likely to cause infiltration problems if the ECw is less than 0.4 dS/m, but not if the ECw is greater than 1 dS/m.

The same guidelines are used to interpret the salinity and sodicity levels of a soil water sample obtained from a saturated soil paste of a surface sample. These guidelines do not apply to samples (and associated soil water samples) obtained deeper than three inches below the soil surface.

Deeper soil strata are less sensitive to exchangeable sodium or to the lack of sufficient salinity to counteract the effects of exchangeable sodium (Shainberg and Letey, 1984). Beneath the soil surface, water quality effects are not enhanced by the action of irrigation water as it flows along the soil surface or by the beating and sorting action of water drop impact.

Table 3.2 provides only guidelines. Judgment also is required since no general guidelines apply to all soils (Pratt and Suarez, 1990). Although changes in salinity and sodicity have similar effects on all soils under laboratory conditions, the combination of salinity and sodicity which results in a given reduction of water flow through soil columns varies from one soil to the next (Figures 2a and b, section 2). If water quality is a potential problem, read section 3.4

3.4 Soil Salinity and Sodicity

You have reached this section for one of two reasons:

1- Irrigation water salinity (ECw), sodicity (SAR or SARadj), or both indicate they may be causing a water penetration problem.

2- Salinity (ECe) and sodicity (SAR) of the soil water require testing to eliminate them as a cause of poor infiltration.

Poor infiltration occurs when SAR of the soil becomes too high for ECw of the irrigation water to counteract. Causes of high SAR levels include:

- Insufficient and frequent irrigation.
- Poor infiltration.
- A high water table.
- Water evaporation at the soil surface. Evaporation increases both soil salinity and sodicity. Continued irrigation can result in additional increases if this water also evaporates.
- Native, sodic soils. Although the classic signs of high soil sodicity are uncommon in irrigated areas of California, the following clues indicate high sodicity is a problem:

  Black surface coatings consisting of dispersed organic matter on the soil surface.

  Pink color when phenolphthalein solution is added to pools of water on the soil surface, indicating a soil pH greater than 8.5.

3.4.1 SOIL ANALYSIS

A laboratory analysis of soil samples is the only way to determine soil salinity and sodicity. The laboratory will:

1- Prepare a water-saturated soil paste and extract a water sample using vacuum. The phrase "saturation extract" is often used to describe this water sample.

2- Measure the extract's ECe and the concentrations of calcium, magnesium, and sodium.

3- Calculate the sodium adsorption ratio (SAR). The SAR of a saturation extract is about equal to the percent of exchangeable sodium adsorbed by soil particles.

The laboratory should not calculate an adjusted sodium adsorption ratio because the saturation extract has had an opportunity to equilibrate with soil lime and other soil minerals. The electrical conductivity of the saturation extract (ECe) is the standard measure of soil salinity, and SAR is the standard measure of soil sodicity.

These values are most accurate when the laboratory makes the extract with the least amount of water possible. Extracts with greater dilution, such as soil water ratios of 1:5 or 1:10, are easier to make but give less accurate ratios. Higher dilutions affect SAR and ECe in different ways. If higher dilutions are used, the guidelines in Table 3.2 will not apply. For a complete description of the laboratory methods, read Chapter 10, "Field and Laboratory Measurement," by Robbins and Wiegand (1990).

Soil samples must be taken from several locations because ECe and SAR values will vary throughout the field. Coefficients of variation for ECe exceeding 50% are common (Oster and Wood, 1977, Hanson and Grattan, 1990). Sampling from similar areas, such as from the bed or the furrow bottom, within the wetted perimeter of a sprinkler, or within areas of similar soil textures will reduce variability. We recommend that each soil sample offered for analysis be a composite of at least nine locations with similar characteristics.

When to sample also must be considered. Sampling after the summer irrigation season would be appropriate to assess possible effects of winter rainfall on soil crusting, erosion, and runoff. It would also be the time when irrigation water quality would have the maximum effect on soil water quality near the soil surface. Sampling after the rainy season ends would indicate how effective the rain has been in lowering ECe and SAR.

Soil samples also must be taken from several depths because each level yields different information. For example,

- A surface sample from the 0-3 inch depth provides ECe and SAR values to compare to those of the irrigation water.
- Comparisons of ECe and SAR samples obtained within the 0-12 inch depth to those of the 12-24 inch depth will show the direction of water movement and whether adequate leaching has occurred in the upper portion of the root zone. ECe and SAR will increase with soil depth when leaching is occurring.
- Samples from deeper layers are needed when auger holes or backhoe pits reveal stratification, soil compaction, hardpan, or dry soil.

To obtain soil samples for analysis,

- Collect soil from five to ten sites that have similar soil irrigation and vegetation characteristics.

- Mix thoroughly equal amounts of soil from each site collected at the same depth to make a composite sample of about 1/2 pound.

3.4.2 INTERPRETATION

Surface samples taken after the irrigation season but prior to any rainfall will indicate that irrigation water quality is not a problem if ECe and SAR of the saturation extract are equal to or less than the ECw and SAR (or SARadj) of the irrigation water. Under these circumstances, both ECe and SAR should increase with depth. If ECe and SAR of the saturation extract are greater than the ECw and SAR (or SARadj) of the irrigation water, water quality is likely part of the problem.

Even when the ECe and SAR of saturation extracts obtained from surface soil are about the same as those of the irrigation water, soil conditions below the surface should be assessed. Sodicity levels four or more inches below the surface are acceptable if SAR is less than 15 times ECe. If SAR is greater than 20 times ECe, however, sodicity is too high and reclamation is needed.

Rainfall will affect the ECe and SAR of surface samples. Two inches of rainfall that infiltrate are sufficient to leach the surface two to four inches of soil. Consequently, ECe will be lowered, and values considerably less (from 0.1 to 0.25 x ECw) than ECw are expected where irrigation water quality is not a problem. SAR, however, decreases less rapidly, and values of 0.5 to 0.8 x SAR of the irrigation water are expected where water quality is not a problem. Consequently, SAR is a better indicator of past infiltration problems due to irrigation water quality than ECe if surface soil samples are obtained after two or more inches of rainfall has occurred.

If salinity or sodicity are problems, go to section 4.1 for possible solutions.

3.5 Soil Texture

You may have been directed to this section because you need to determine soil texture to estimate the soil water content. You also may want to know what linkage might exist between soil texture and water penetration problems.

The amount of sand, silt, and clay in a soil determines the soil texture classification. Soil texture can be estimated by feel, inferred from county soil survey reports published by USDA-SCS, or determined precisely in a laboratory.

3.5.1 DETERMINATION

FEEL METHOD

To estimate soil texture by feel, wet a tablespoon of soil in your hand with enough water to make a sticky mass. Manipulate it with thumb and forefinger until smooth. The more clay in the sample, the stickier it will feel, the harder it will be to work, and the more pliable (moldable) when moist (Figure 3.2 and 3.3).

Figure 3.2. A clay loam texture will make a ribbon when moistened and pushed between thumb and forefinger.

Figure 3.3. A sandy loam textured soil will not form a ribbon when moistened and rubbed between thumb and forefinger.

A ball formed of the wet sample is:

- Mostly clay if it is stiff but moldable.
- Mostly silt if it is easy to flatten and pulls apart with large cracks forming at the edges.
- Mostly sand if it will not hold together.

Table 3.3 lists the characteristics of soil textures used to identify soil textures by feel.

Table 3.3. Soil texture characteristics.

SOIL TEXTURE CLASS	Feel characteristics
SAND AND LOAMY SAND	Crumbles very easily when dry. Feels gritty; single-grained when moist. A ball will form when moist soil is squeezed in hand. The ball cannot be handled without breaking. No ribbon can be formed
SANDY LOAM	Feels gritty, but when moist, holds together better than coarse loamy sand. Fine sandy loam holds together better than coarse sandy loam. You can feel that particles finer than sand are present, but the sand still predominates. No ribbon can be formed.
LOAM	A loam can be 1/4 to 1/2 sand, but most of the grittiness is masked by the silt and clay contents. A moist loam is fairly smooth, not gritty, not sticky, and somewhat plastic. A short ribbon can be formed, but it will split readily and break off when about 1/2 inch long.
SILT LOAM	Dry silt loam feels like talcum powder when crushed. When moist, it is very smooth and slick. It is not sticky and will not cohere enough to make a good ribbon.
CLAY LOAM	Moist clay loam is definitely sticky and plastic. A moderately strong ribbon is easily formed but will break away when about 3/4 inch long.
CLAY	Moist clay is very plastic and coheres very well. Ribbons longer than 1 inch can be formed. It is often difficult to moisten a hard lump of dry clay in your hand to get a plastic mass. It must be soaked or ground first.

USDA-SCS SOIL SURVEY REPORTS

There are individual reports for almost every county in the state. These reports have maps that list soil textures for representative horizons of each soil series. Read section 3.8 if you are unfamiliar with these reports.

LABORATORY METHODS

Hydrometer and pipette methods are used to determine soil texture (Gee and Bauder, 1986). These methods require laboratory facilities.

3.5.2 INTERPRETATION

Here we discuss how soil texture at or near the soil surface affects water penetration. See section 3.7.1 and section 4.2 for the effects of soil texture below the soil surface.

In California, soils high in silt and sand or low in swelling clays have low shrink-swell properties. Surface crusts which form on these soils do not crack upon drying. Cracks are extremely important for increasing the initial entry of water into dry crusted soils. They increase the total surface area for infiltration 3 to 5 times. The lack of cracks is one reason soils along the east side of the Central Valley have low water intake rates. There, the predominant clay minerals are hydrous mica and vermiculite, which do not swell upon wetting or shrink upon drying.

Similar problems exist in other parts of the world. For example, Ben-Hur et al (1985) found that soils in Israel with approximately 20% clay tended to have the most crusting problems. Soils with < 20% clay had fewer problems, because there was less clay to disperse and to clog pores. Soils with >20% clay had fewer crusting problems. The additional clay helped to create stable structures that resisted destructive forces. The presence of lime ($CaCO_3$) in the soils tested did not influence the rate at which they crusted. In those cases where saline water (SAR = 2, ECe = 5 dS/m) was used to irrigate the soils, the more silt in the soil, the more quickly a crust formed. Laboratory-made soil mixtures containing between 20 and 50% silt showed that as the silt content increased, the saturated hydraulic conductivity decreased (Grismer et al, 1989).

Ben-Hur et al (1989) suggest that soils with high shrink-swell clays such as montmorillonite will crack upon drying, thus improving the infiltration rate of those soils that tend to crust. Soils with vermiculitic clays will not crack as much and will remain crusted with slow infiltration. Such soils may require more physical manipulation to maintain infiltration during the growing season. Because vermiculite forms from mica and is platy, the presence of vermiculite in soils on the east side of the Sacramento and San Joaquin Valleys indicates there is the potential for serious crusting problems, even in sandy soils (perhaps even more so in sandy soils).

If soil texture is a potential problem, see section 4.1.2 or 4.1.3 for possible solutions.

3.6 Surface Conditions

Frequent causes of slow water penetration are poor physical conditions near the soil surface. These conditions, primarily compaction and crusting, are the result of cultivation and irrigation.

3.6.1 CRUSTING

Two kinds of soil crusts cause slow water penetration problems.

1- A thin surface crust formed by the beating action of rain and water drops on the soil surface or by the collapse of soil surface structure upon wetting. The soil particles are rearranged with a consequent reduction in the number and size of large pores. Upon drying the crust becomes hard. In the scientific literature this kind of crust is called a structural crust (Figures 3.4, and 3.5).

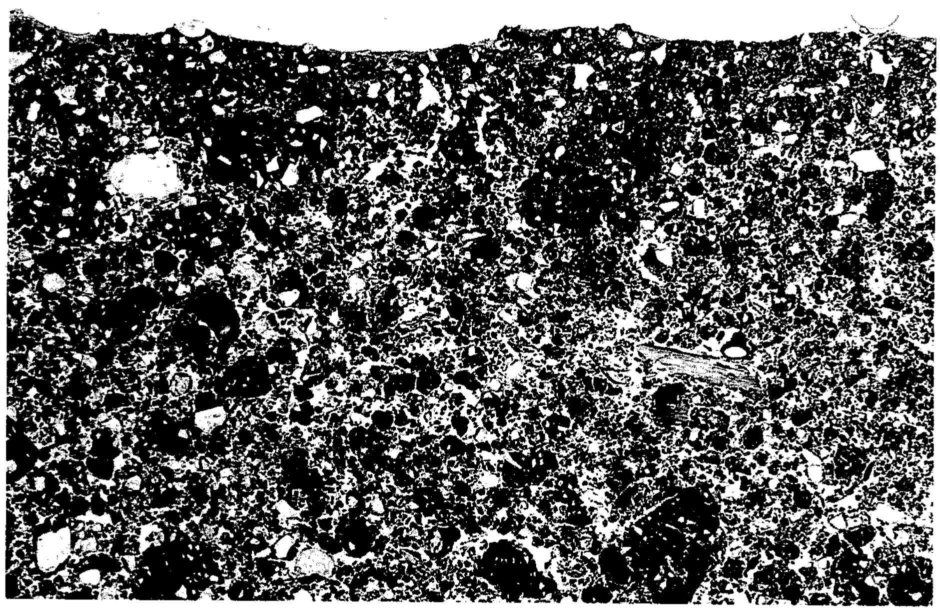


Figure 3.4. This is a photograph taken through a microscope showing the details of a structural crust. The area shown is 1.4 inches long and 0.9 inches wide. The crust is the thin layer at the soil surface. Note the lack of porosity (white areas) in the upper 0.05 inches of this sample.

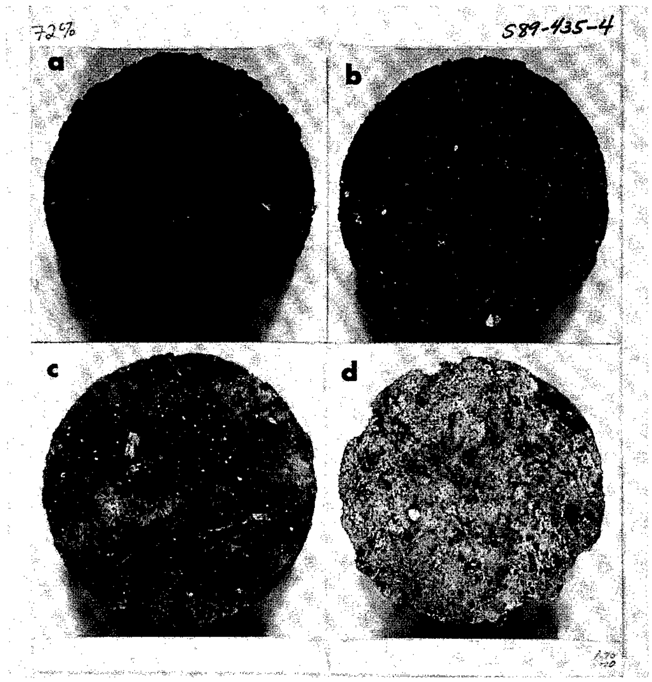


Figure 3.5. Four stages in structural crust formation. (a) uncrusted surface, (b) 10 minutes of rainfall, (c) 25 minutes of rainfall, (d) 90 minutes of rainfall. (Photo from Moore and Singer, 1990).

2- A thicker crust formed when sediment-laden water infiltrates into the soil leaving behind particles that form a crust. In scientific literature this kind of crust is called a depositional crust (Figures 3.6 and 3.7).

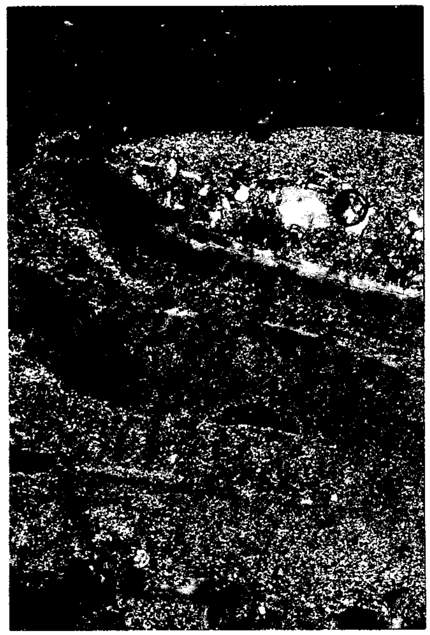


Figure 3.6. A photo taken through a microscope (60x) showing three clay layers (orange) and lack of porosity of a depositional crust formed in a laboratory by allowing three separate sediment laden irrigations to infiltrate into the soil.

Knowing which kind of crust is causing slow water penetration is useful because different remedial procedures apply. Flow chart 9 will help you identify the type of crust and direct you to the appropriate subsection for prevention techniques and solutions.

Figures 3.8a and b are drawings that illustrate both types of crusts.

Figure 3.7. A depositional crust in an orchard. The lens cap is 55mm wide. The marks on the soil surface are from the disk.

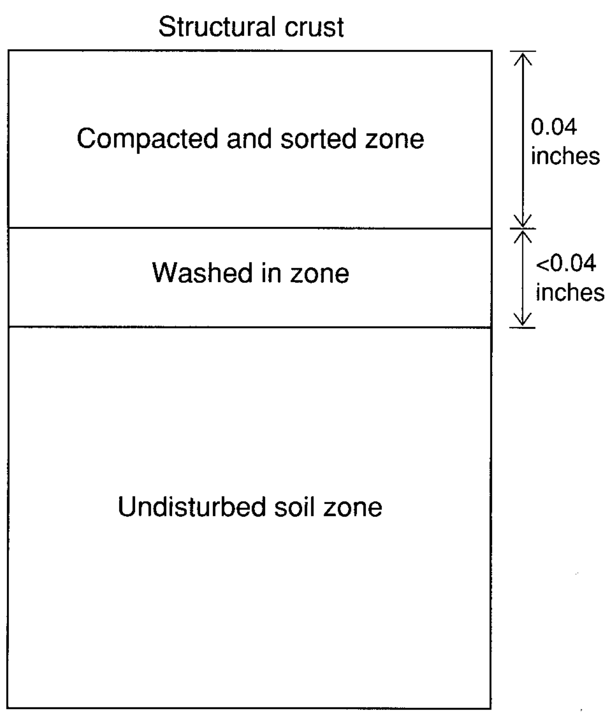


Figure 3.8a. Diagram of a structural crust.

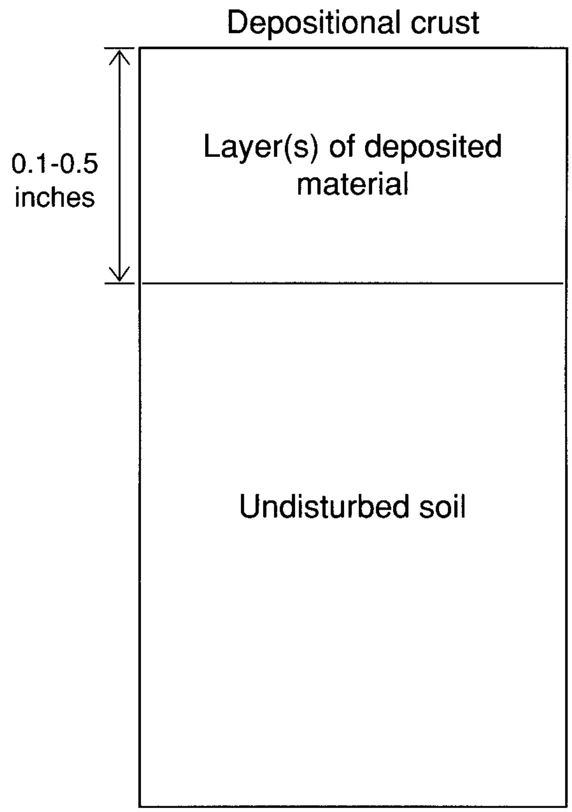


Figure 3.8b. Diagram of a depositional crust.

3.6.2 COMPACTION

Compaction is caused by machine traffic and tillage. It occurs within and immediately below the depth of tillage. Soil compaction results when an applied force causes particle rearrangement and increases bulk density. This increase in bulk density is accompanied by a decrease in the total volume of soil pores and often by an increase in the number of small pores distributed through the soil. Figure 3.9 illustrates a typical plow pan and its relation to soil depth and soil density. The bulk density from the soil surface to a foot below where tillage occurs is the most definitive measurement of compaction.

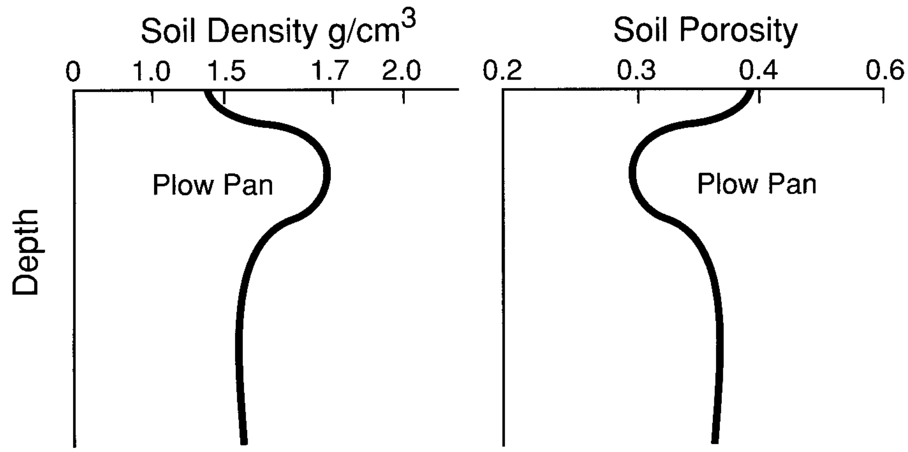


Figure 3.9. Bulk density and soil porosity as functions of depth. Note that density increases and amount of pore space decreases in the plow pan that has been created by soil compaction.

Compaction is generally easy to recognize because the soil above and below the compacted layer is softer than the compacted layer. Sometimes, however, compaction is confused with moist surface soil lying over dry subsoil. What may feel like compaction is only a contrast between wet and dry soil.

Other visual clues include:

- Water standing in wheel tracks or tracked areas after all other water has infiltrated.
- Roots which reach the same shallow depth and then grow horizontally instead of vertically.

Other physical clues include:

- A change in how easily a metal probe inserts into the soil.
- A change in characteristics of a shovelful of soil. Compacted, moist soil falls off the shovel in hard, large blocks while soil that is not compacted falls off in loose, small pieces.

If compaction is a potential problem, go to section 4.1.3 and 4.2 for possible solutions.

3.7 Subsurface Conditions

Slow water penetration can be caused by soil stratification, claypan, cemented hardpan, and bedrock. Making sure that subsoil conditions are indeed causing slow water penetration is important because the remedies are expensive: deep tillage, ripping, or slip plowing.

To determine subsurface soil conditions:

1- Check USDA-SCS soil survey reports (section 3.8). Although the information is frequently too general to avoid on-site investigation, it is advisable to consult the reports before selecting backhoe sites.

2- Dig some pits, preferably with a backhoe; observe the soil profile along the pit walls and identify soil textures.

3.7.1 STRATIFICATION

Alluvial soils along major rivers are stratified. These soils have layers with abrupt changes in texture beneath the surface (Figure 3.10). These layers prevent the uniform flow of water and cause zones of poor aeration.

- Clay layers can restrict water movement causing perched water tables, and poor aeration.

- Sand layers can cause the same problems because the overlying soil must reach saturation before water will flow into the sand layer.

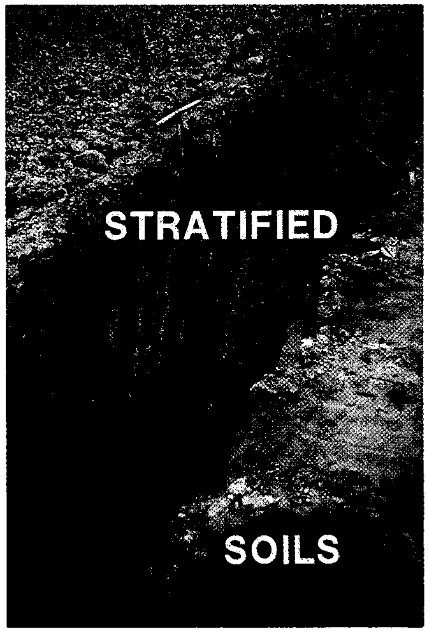
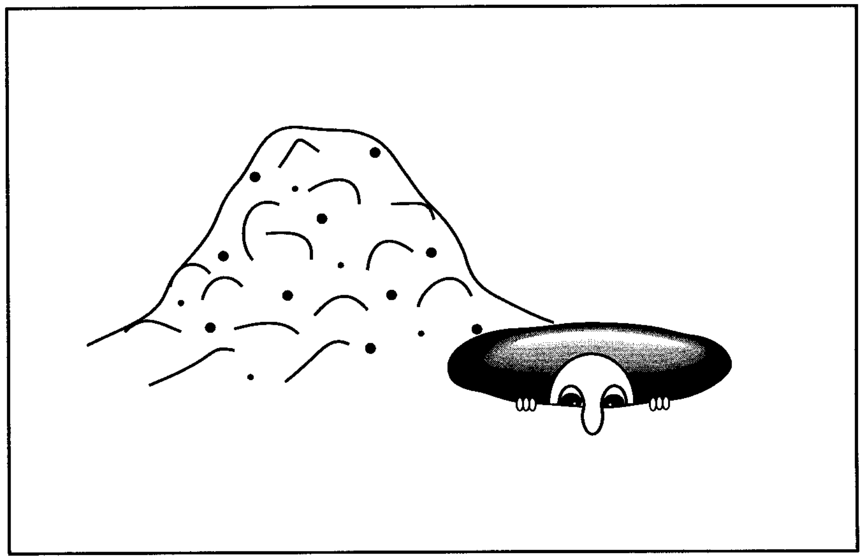


Figure 3.10 Stratification in an alluvial soil is readily apparent when the layers are thick and colors or textures contrast strongly. Photo credit, W. E. Wildman.

If this condition exists in your field, check section 4.2.2 for possible solutions.

To determine if stratification is present, dig a soil profile to a depth of 5 or 6 feet. When the layers are thick, they are readily apparent (Figures 3.10 and 3.11). When the layers are thin and the contrast between layers is slight, the only way to determine stratification is to identify soil textures by feel (see section 3.5.1).



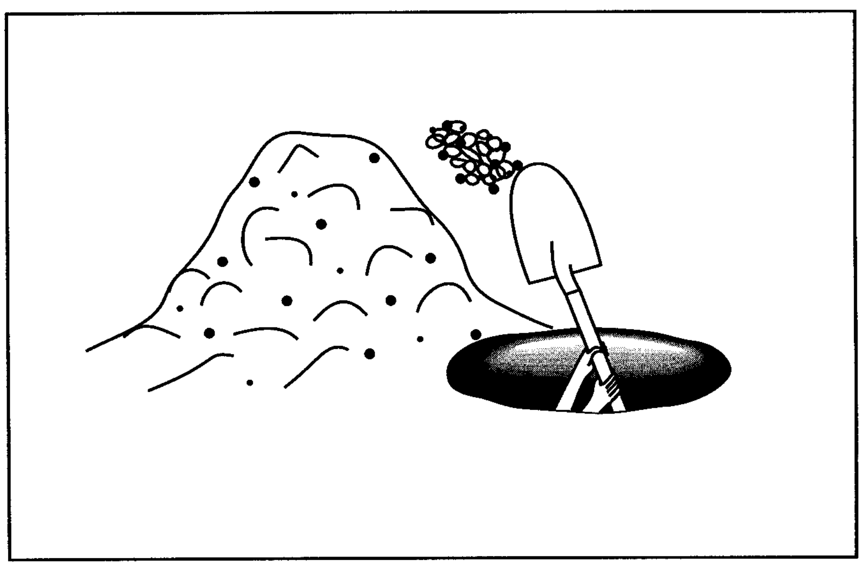


Figure 3.11 Stratification in an alluvial soil. In the center of the photo the stratification has been destroyed by deep tillage. Photo credit, W. E. Wildman.

3.7.2 CLAYPAN AND CEMENTED HARDPAN

Claypan is a subsoil clay layer. Typically the clay layer starts rather abruptly at a depth of 12 to 24 inches (Figure 3.12) and gradually grades into a clay loam, loam, or sandy loam at lower depths.

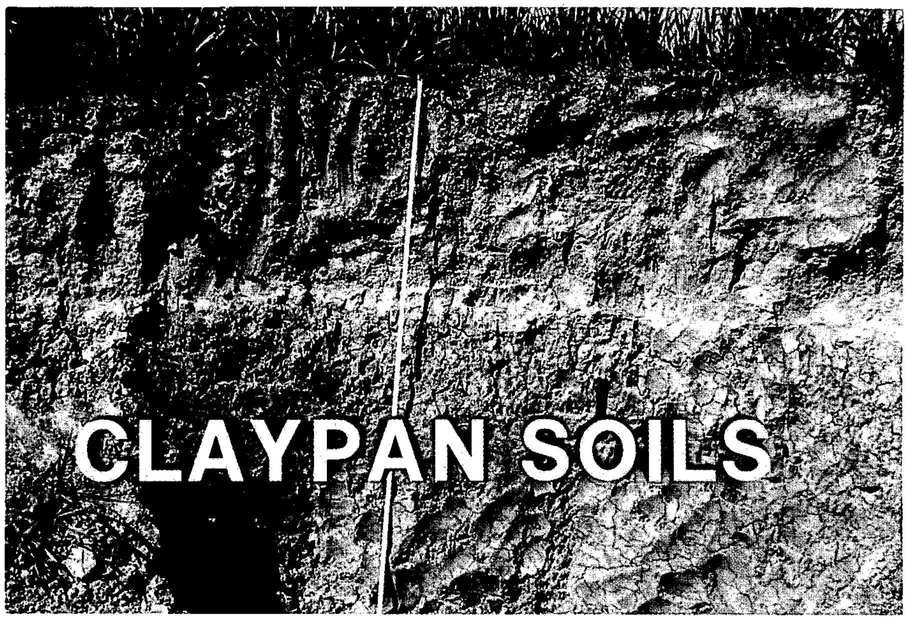


Figure 3.12. Photo credit, W. E. Wildman

Cemented hardpan occurs below the surface and consists of soil materials cemented by silica and $CaCO_3$ in arid and semiarid climates and by iron and aluminum oxides in tropical climates.

Figure 3.13. Photo credit, W. E. Wildman.

To distinguish claypan from cemented hardpan, drop a piece of the layer in a bucket of water. If the sample softens and falls apart, it is claypan; if it does not, it is cemented hardpan.

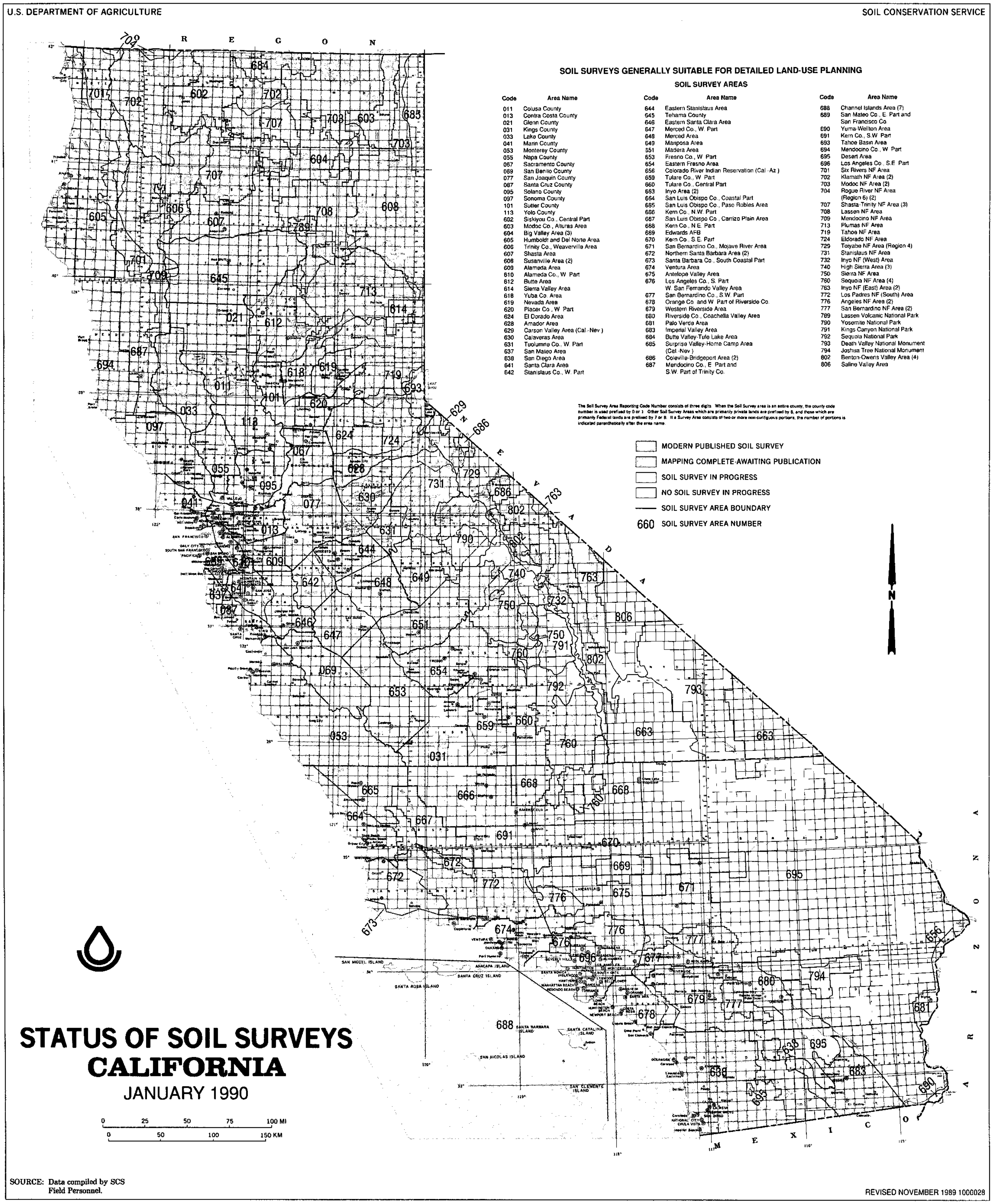
3.7.3 BEDROCK

If dynamite is required to break it, it's bedrock. If you have a shallow soil over bedrock, improved water management (section 2.1), changing irrigation systems (section 4.3), and changing crops (section 2.4) are possible ways of living with the problem.

3.8 Survey Reports

The USDA Soil Conservation Service prepares and publishes soil survey reports for individual counties. The reports give information on soil profiles and indicate how soil texture may change with depth for each soil series. They are especially useful in determining the presence of such conditions as stratification, clay layers, hardpan, and bedrock. These reports and assistance in interpreting them are available from the local Soil Conservation field and area offices. UC Cooperative Extension personnel also can help in interpreting survey reports. Phone numbers for persons in both services are listed in the resource directory.

The areas in California that have been mapped and published are shown in Figure 3.14.



USDA-SCS-NATIONAL CARTOGRAPHIC CENTER, FT. WORTH, TX.-1992

3.8.1 PUBLISHED REPORTS

With the appropriate survey report in hand, follow the steps below to determine the soil conditions in the area you are concerned about:

1- Look at the colored general soil map (for example, Figure 3.15) to find the number of the detailed map and to see the general soil category for your area.

2- Locate the specific area on the appropriate detailed map, using roads, towns, building locations, and township boundaries as a guide. Then find the appropriate map unit or units marked off with dark lines. These map units are labeled within the lines by numbers in the latest surveys and with letters and numbers in older surveys (Figure 3.16). Figure 3.16 is a portion of the detailed map number 45 for Yolo County, California. It represents an area one mile on a side. The large number 30 is the section number. The thin dark lines are soil boundaries.

3- Use the index or key to the symbols on the map units to find the name of the soil corresponding to the map unit.

4- Read the soil description in the report. The letters BrA, Rg, Mf, Ms, and Ya in Figure 3.16 are shorthand notations for the soil map units that are found inside the soil boundaries. BrA is Brentwood silty clay loam, Rg is Rincon silty clay loam, Mf is Marvin silty clay loam, Ms is Myers clay, and Ya is Yolo silt loam. You can see that the map is produced on an aerial photo that contains information about the land use at the time the photo was taken.

5- Look at the tables of data and interpretation for the soil.

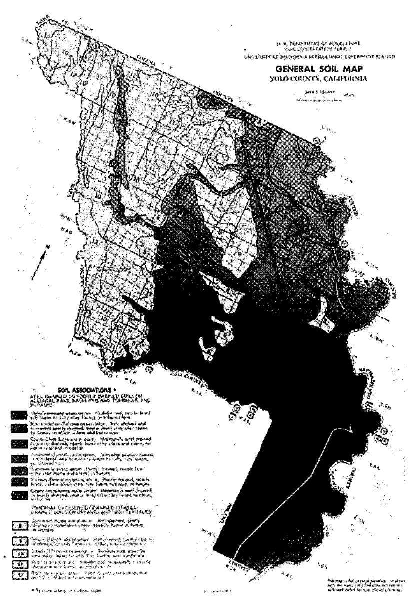


Figure 3.15 General soil map from Yolo County California. Soil associations show groups of soils that occur together on the landscape.

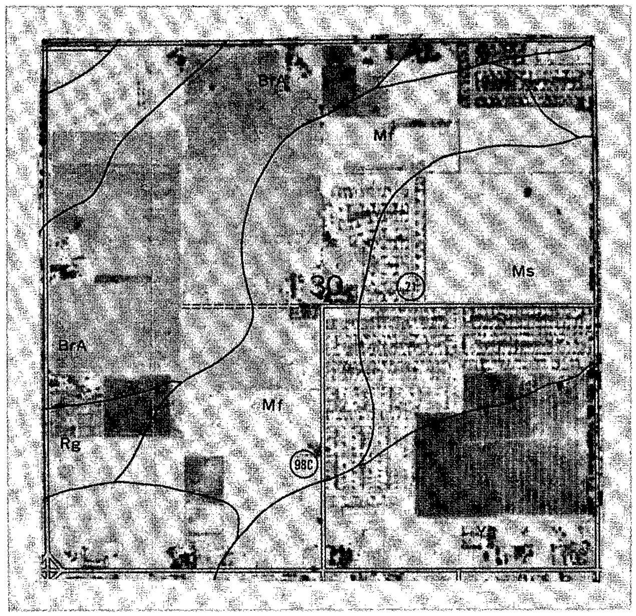


Figure 3.16. This is a 640 acre (square mile) portion of a detailed soil map from the Yolo County California soil survey report. Roads, houses, and crops are easily seen on the aerial photo base. The section number (30) and soil map units (Ms, Mf, BrA, Rg, and Ya) are identified in block.

3.8.2 UNPUBLISHED REPORTS

If the area of concern has not been surveyed and described in the latest reports, talk with either the conservationist or soil scientist at the nearest Soil Conservation Service office. The soil scientist may have a completed but unpublished map of the area and will also have information on surveys in progress and can help interpret soil conditions in areas contiguous to mapped areas. Often contiguous areas have similar soil conditions.

3.8.3 FIELD INVESTIGATIONS

If no survey report is available for your area, field investigations will be necessary. They also will be useful in confirming what survey reports have predicted. Although backhoe excavations are best, auger holes and hand dug pits will often yield enough evidence for confirmation of survey report information.

To arrange for a field investigation, call the farm advisor or specialist at the nearest UC Cooperative Extension office and dig several backhoe pits for inspection. To determine the presence of stratification and horizons, these pits should be 3 to 4 feet wide, 10 to 12 feet long, and 3 to 4 feet deep. Also the pits should be opened no more than a day or two before inspection because dry pit walls will give misleading impressions.

Once you have soil information, return to the key at the front of this section to locate appropriate sections to read in this manual.

REMEMBER SAFETY FIRST

Soil walls can fail and slump into the trench. Enter only trenches that are at least as wide as they are deep. In wet or recently irrigated soil, narrow trenches (2-3 feet) and deep trenches (greater than 4 feet) are unsafe.

SECTION 4
SOLUTIONS

4.0 Introduction

This section of the manual describes various solutions to problems of slow water penetration. These solutions have been used in California or elsewhere, as reported in the literature.

At the end of each section is a research summary. If you need more information about a study, look up the name and year in the citations section at the back of the manual.

The solutions are grouped under three main headings: surface problems, subsurface problems, and changes in irrigation systems.

4.1 Surface Problems

"Go to Section 4.1" is the most common instruction in this manual. Reference to this section is made frequently because water infiltration through the soil surface is crucial to all irrigation systems except subsurface drip. The soil surface and the soil immediately beneath is subjected directly to the effects of applied water and to machine traffic. Both can greatly reduce the ability of soil to conduct water.

Surface problems include crusts and compaction. Structural crusts are formed by the impact of water drops from sprinklers and rain and by the collapse of soil aggregates upon wetting. Although compaction occurs through and below the zone of cultivation, we have included it in the surface problem section.

If the problem with slow water penetration is caused by either crusting or compaction, solutions include the following three management approaches:

1- Use chemical amendments to change soil surface and irrigation water chemistry.

2- Add organic matter to increase stability of soil aggregates or soil structure.

3- Till to break up crusts and compaction.

4.1.1 CHEMICAL AMENDMENTS

Several chemical amendments can improve water infiltration. They improve the chemical make-up of either the soil or water primarily by boosting the calcium content. This is beneficial for two reasons:

1- It increases the total salt concentration, or electrical conductivity (ECe) of the soil water.

2- It decreases the sodium adsorption ratio (SAR) of the soil water and consequently the level of exchangeable sodium in the soil.

Both effects can increase water penetration, particularly if slow water penetration is a problem. Both enhance the stability of soil aggregates. Thus, they decrease the formation of hard, dense soil crusts and the blockage of large, water-conducting soil pores by fine clay particles. Amendments are added to the soil, water, or both.

GYPSUM

Gypsum is the amendment most often used because it releases abundant quantities of calcium, is inexpensive, and is easy to apply.

Amendments such as sulfur, sulfur dioxide gas, lime sulfur, potassium and ammonium thiosulfate, and sulfuric acid release calcium by dissolving soil lime (Table 4.1). Using lime ($CaCO_3$) on a neutral or acidic soil (pH less than 7.5) can also increase calcium levels in the soil and at the same time also increase soil pH. Adding lime will do neither if the soil pH is greater than 7.5.

Gypsum is a mineral product that is mined and ground to different size grades. When added to either the water or soil, gypsum provides calcium. How rapidly gypsum dissolves depends on the degree of crystallization and on the size of the mineral particles (Frenkel and Fey, 1989). Thus, finely ground gypsum is most effective for solving water infiltration problems. Gypsum from mines is highly crystallized.

Phosphogypsum, a by-product of the manufacture of phosphorous fertilizer, is not highly crystallized and dissolves faster than mined gypsum. In addition, it adds small amounts of phosphorus to the soil. However, it is not currently available in California. If it were available, it would be better than mined gypsum for application directly to soil surface.

Whether it is best to add gypsum to the irrigation water or to the soil depends to some extent on the source of the problem. The guidelines are:

- Add gypsum to the irrigation water if its electrical conductivity (ECw) is less than 0.5 dS/m or if its adjusted sodium adsorption ratio, SARadj, is 5 to 10 times greater than ECw (Figure 4.1).

- If addition to the irrigation water is not possible, application of gypsum to a freshly tilled soil surface is a less desirable alternative. Applied to the soil, gypsum soon dissolves and leaches out, allowing the soil to seal again.

- Add gypsum to the soil, preferably immediately after tillage, if a saturation paste extract made of a soil sample from the surface has a sodium adsorption ratio, SAR, that is 5 to 10 times greater than ECw.

- Add gypsum and incorporate with tillage if a saturation paste extract made of a soil sample from six inches below the surface has an SAR that is 10 to 20 times greater than the electrical conductivity of the extract.

Gypsum application through irrigation water.

- Obtain a machine that mixes finely ground gypsum with water and injects the mixture into the irrigation water (Figure 4.1). Injection of 470 to 940 pounds of gypsum per acre-foot increases the calcium and sulfate concentrations in the water by 2 to 4 meq/L.

Figure 4.1. Machine for dissolving and injecting gypsum into irrigation water. No endorsement of company named in the picture is intended. Photo credit, Jerry Rivers.

Rates of 470 to 940 pounds per acre-foot of water are reasonable over the long term. However, the machine can inject at higher rates. A one-time application at rates of 1410 to 1880 pounds per acre-foot may result in more rapid improvement of water penetration.

- Begin gypsum injection immediately following tillage and continue for several irrigations.

To check for effectiveness:

- Check the electrical conductivity of the irrigation water, ECw, before and during gypsum treatment. Treatment at rates of 470 to 940 pounds per acre-foot should increase ECw by 0.15 to 0.3 dS/m.

- Maintain an area irrigated with untreated water. For surface irrigation, advance rates of treated furrows should be slower than those of untreated furrows. Recession rates should be faster, and runoff should be reduced. During sprinkler irrigation, surface ponding in untreated areas should occur before it occurs in treated areas. During surface drip irrigation, the area of surface ponding in treated areas should be smaller than in untreated areas.

Increased depth of water infiltration and reduced crop stress are other indicators of improved water penetration.

To maintain the improvement in infiltration achieved after several months of continuous gypsum application:

- Do not stop application completely. Without continued treatment infiltration gradually returns to the rates that existed before treatment.
- Reduce applications to three out of four or two out of four irrigations. With experience and proper monitoring, maintenance of infiltration rates may be possible without continuous application.

Research has demonstrated the effectiveness of adding gypsum or other calcium-producing agents to the irrigation water.

- In a study of a border irrigation system for walnuts, adding gypsum to the irrigation water increased the calcium levels in the upper two feet of soil and reduced the recession time from six days to two or three days (Fulton, 1992). The same was true for furrow irrigated cotton.
- In a two-year study conducted in a drip irrigated orchard in Tulare County, California, adding calcium continuously to the irrigation water doubled or tripled infiltration rates over untreated, low-salt water (Peacock et al, 1989).

Table 4.2. 1986 Lindcove treatments and grouped average infiltration rates for period 6/11 - 8/6.

Treatments	Avg. infiltration rate inches/hr[f]
Calcium nitrate, undisturbed	0.18 a
Gypsum, disturbed	0.17 a
Gypsum, undisturbed	0.15 ab
Polyacrylamide, disturbed	0.11 bc
Polyacrylamide, undisturbed	0.11 bc
Control, disturbed	0.10 bcd
Control, undisturbed	0.09 cd
Non-ionic surfactant, undisturbed	0.08 cd
Non-ionic surfactant, disturbed	0.06 d
LSD .05	0.05

[f] Numbers followed by the same letter are not significantly different ($P \leq 0.05$)

Table 4.3. 1987 Lindcove treatments and grouped average infiltration rates for period 6/24 - 8/19.

Treatments	Avg. infiltration rate inches/hr[f]
Calcium acetate, daily	0.27 a
Calcium nitrate, daily	0.20 ab
Calcium chloride, daily	0.16 bc
CAN-17, daily	0.16 bc
Calcium nitrate, biweekly	0.14 bcd
Calcium nitrate, single application	0.09 cde
Control	0.09 cde
CAN-17, biweekly	0.07 de
CAN-17, single application	0.05 e
LSD .05	0.08

[f] Numbers followed by the same letter are not significantly different ($P \leq 0.05$)

Gypsum application to soil surface:

- Use one to four tons per acre of finely ground gypsum.
- Apply gypsum immediately after tillage. Tillage after application reduces effectiveness, particularly if the gypsum is mixed into more than one to two inches of soil.
- Apply gypsum after tillage only when infiltration rates become too slow to meet crop needs. Applying gypsum before then is ineffective because the gypsum dissolves and moves downward from the soil surface, the zone limiting infiltration for surface problems.

Tillage may not be possible because of other cultural practices or because crop growth restricts access. Application of gypsum to an untilled surface will be less effective but may be better than no gypsum treatment.

Figure 4.2. Gypsum application under drip lines in a vineyard. Application is being made to the soil surface where irrigation water is to be applied. Photo credit, Bill Peacock.

To check for effectiveness:

- Maintain an area irrigated with untreated water. For surface irrigation, advance rates of treated furrows should be slower than those of untreated furrows. Recession rates should be faster, and runoff should be reduced. During sprinkler irrigation, surface ponding in treated areas should take longer to occur, and runoff should be less. During surface drip irrigation, the area of surface ponding in treated areas should be smaller than in untreated areas. Increased depth of water infiltration and reduced crop stress are other indicators of improved water penetration.

- If there are no differences between treated and untreated areas, gypsum is ineffective.

Research on gypsum shows that applying it to the soil is effective where water has low salinity, where surface soil has high sodicity, and where crusting occurs.

- Where irrigation water has low salinity, the application of mined gypsum to the soil surface increases the salinity of the water when it contacts the gypsum and infiltrates into the soil. Since the 1950s farmers using the low salinity water from the Friant-Kern canal have applied mined gypsum to the soil to increase infiltration rates (LAWR, 1984).

- In a sprinkler irrigation study conducted by Oster et al. (1982), applying 1.2 tons per acre of phosphogypsum to the surface of freshly tilled soil with an SAR of 13 increased infiltration from less than 0.06 to about 0.12 inches per hour. The improved infiltration rates were maintained by applying the same amount of gypsum about once every two years.

Figure 4.3. Ponding did not occur after sprinkler irrigation of one inch of water where gypsum was applied to the soil surface.

Growing blando brome, a self-seeding winter annual, was equally effective (Rick Fuller, private communication, 1987). However this practice was discontinued because it aggravated hay fever problems with employees.

- In a study of a prune orchard in the Sacramento Valley, five tons per acre of phosphogypsum applied to the soil surface improved infiltration rates. Mixing five tons into the soil, however, was ineffective (Singer et al, 1984).

- In studies of structural crusts, phosphogypsum improved water penetration by increasing the electrolyte concentration thereby opening the crust structure (Shainberg and Singer, 1985 and 1986; Southard et al, 1988).

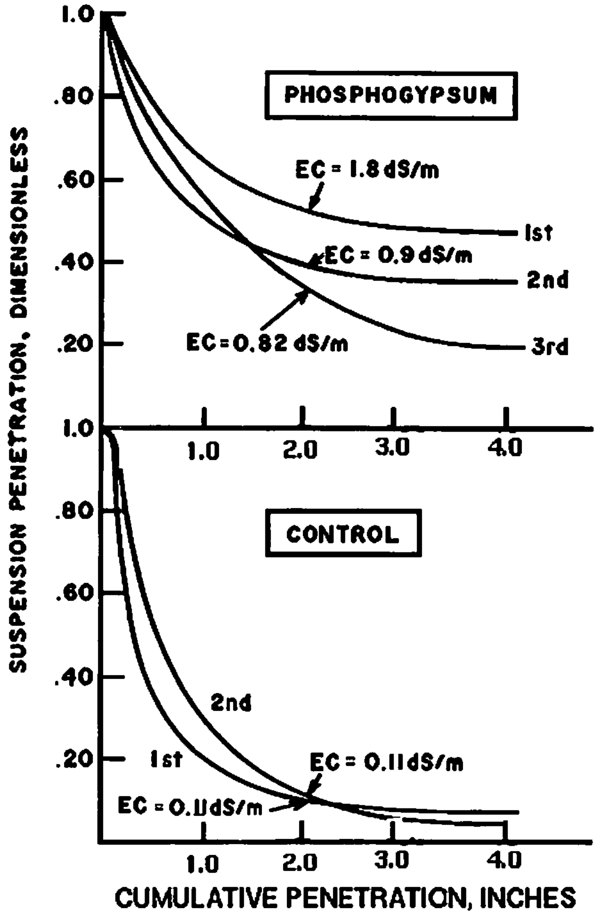


Figure 4.4. Depositional crusts were more permeable in a laboratory experiment in which phosphogypsum was applied to the soil surface. Note that one phosphogypsum application helped to maintain relative infiltration rates compared to the control after three irrigations with sediment laden water (adapted from Shainberg and Singer, 1985).

- In studies of acidic, neutral, and alkaline soils, surface applied gypsum increased infiltration rates under irrigated and rainfall conditions (Shainberg et al, 1989).

- In a study of deep highly weathered soil in South Africa, plots treated with phosphogypsum and plots treated with organic mulch both had infiltration rates three to five times higher than untreated plots. The treatments nearly saturated five inches of surface soil with calcium, and the phosphogypsum treatment also increased phosphorus levels. However, a loss of potassium and magnesium caused concern (Van der Watt and Claassens, 1990).

Soil or water treatment:

Elemental sulfur, polysulphides, and thiosulfates can reduce exchangeable sodium levels (Table 4.1) in soils that contain lime or calcium carbonate. Oxidation of these amendments by soil microorganisms generates sulfuric acid. Sulfuric acid reacts rapidly with calcium carbonate ($CaCO_3$) in the soil, releasing calcium that exchanges with sodium adsorbed on soil clays. Since microbiological activity increases with increasing temperature, these amendments are most effective during summer months.

The pounds of amendment required to replace exchangeable sodium (Column 4 of Table 4.1) depend on different reactions (footnotes a-d), reaction efficiencies (footnote e), and cation exchange capacity and desired change in exchangeable sodium or sodium adsorption ratio of the soil (footnote f).

Elemental sulfur is applied directly to the soil and requires tillage to mix the sulfur into the soil. Polysulfides, thiosulfates, and sulfuric acid can be applied to the irrigation water or to the soil. Special equipment is required for sulfuric acid.

Because of the complex chemistry and alternative modes of use, we recommend obtaining advice about amendment alternatives and requirements from UC farm advisors, SCS agronomists, and consultants.

Table 4.1. Amounts of sulfur containing amendments required to replace 1 meq/100 g of exchangeable sodium or to increase calcium content in irrigation water or soil solution by 1 meq/L

Chemical name	Trade name/ composition	Tons equal to one ton of sulfur	Pounds[f] required per acre to replace 1 meq/100 g of exchangeable sodium[g] in 6 inches of soil	Pounds[f] required per acre-foot of water to obtain 1 meq/L of calcium	Chemical reactions that occur in soils
sulfur		1.00	320	43.5	$2S + 3O_2 + 2CaCO_3 + 4NaX = 2CaX_2 + 2Na_2SO_4 + 2CO_2$
gypsum		5.38	1720	235	$CaSO_4 + 2NaX = CaX_2 + Na_2SO_4$
potassium thiosulfate	KTS 25%K[a], 17%S[b]	5.87	1880	255	$K_2S_2O_3 + 2O_2 + CaCO_3 + 4NaX = CaX_2 + 2KX + 2Na_2SO_4 + CO_2$
ammonium thiosulfate	thio-sul 12%N, 26%S[b]	3.82[c] 2.55[d]	1220 814	166 111	$(NH_4)_2S_2O_3 + 2O_2 + CaCO_3 + 4NaX = CaX_2 + 2NH_4X + 2Na_2SO_4 + CO_2$
ammonium polysulfide	nitro-sul 20%N, 40%S[e]	1.59[c] 1.17[d]	510 375	69.1 51.0	$(NH_4)_2S_5 + 3NH_4OH + 8O_2 + 4CaCO_3 + 13 NaX = 4CaX_2 + 5NH_4X + 5Na_2SO_4 + 3NaOH + 4CO_2$
sulfuric acid		3.06	980	133	$H_2SO_4 + CaCO_3 + 2NaX = CaX + Na_2SO_4 + CO_2 + H_2O$

[a] One mole of potassium assumed to replace beneficially one mole of exchangeable sodium.

[b] One mole of thiosulfate assumed to result in replacement of one mole of exchangeable sodium by calcium.

[c] One mole of ammonium assumed to replace beneficially one mole of exchangeable sodium.

[d] One mole of ammonium assumed to result in replacement of two moles of exchangeable sodium by calcium. Nitrification of ammonium to nitrate in calcareous soils releases one mole of calcium per mole of ammonium.

[e] One mole of polysulfide assumed to result in replacement of two moles of exchangeable sodium by calcium.

[f] Not all the calcium, or its equivalent in the form of potassium and ammonium, will replace exchangeable sodium. The exchange reactions do not go entirely to completion. The extent of completion depends on replacement energies of calcium, potassium, ammonium, and sodium, and the exchangeable sodium percentage (ESP). More amendment is required than shown in this column. The correction for incomplete reactions involving calcium from gypsum or lime ranges from 1.14 times the amount shown for an ESP (or SAR) of 15 after the reactions are completed to 1.32 for an ESP (or SAR) of 5 after reactions are completed (Oster and Frenkel, 1980).

[g] The amount of exchangeable sodium to replace is the product of the cation exchange capacity times the difference between the initial ESP/100 (or SAR/100) and the desired final ESP/100 (or SAR/100).

Water treatment:

For irrigation water with bicarbonate and with a high adjusted sodium adsorption ratio, injecting sulfuric acid or sulfur dioxide into irrigation water removes bicarbonate from the irrigation water and dissolves $CaCO_3$ in the soil. This reduces the sodicity (SAR) of the soil water. This method is most effective when the water has an ECw of less than 0.5 dS/m, when more than 50% of its anions are bicarbonate, and when there is lime in the soil. Addition of 133 pounds of 100% sulfuric acid to one acre foot of water will remove 1 meq/L of bicarbonate and boost calcium concentrations in calcareous soils by an equal amount (Table 4.1).

How much sulfuric acid or sulfur dioxide to add depends on the soil and is best determined by field experience. Again, an untreated area of the field will be useful in determining how effective the amendment is and how much is needed.

Be careful! Do not add too much sulfuric acid or sulfur dioxide to the water. After more than 90% of the bicarbonate is removed, the pH will drop quickly with additional amendments, and the water can become very corrosive. It may not be necessary to remove 90% of the bicarbonate to achieve sufficient improvement in water penetration.

SOIL CONDITIONERS

Soil conditioners consist of synthetic organic polymers. They can be grouped into two functional categories: 1) water sorbing, and 2) soil gluing. We do not address water sorbing characteristics in this manual. Rather our interest is in the ability or organic polymers to stabilize aggregates or create larger aggregates by "gluing" smaller ones together.

Research studies conducted in the 1950s demonstrated that improvements in soil structure could be achieved by applying several hundred pounds of soil conditioners per acre. Recent research indicates lower rates are effective provided the soil conditioner is applied in the irrigation water. Restricting the treated area to the drip line or seed bed, for example, would reduce rates further. Although these new findings are promising in terms of effectiveness and cost, to date the scientific evidence is not conclusive enough for us to recommend the use of soil conditioners.

Research on soil conditioners indicates the following:

Positive Results

- After furrows are ripped in an Arlington sandy loam to a depth of 7 inches, a one time application of polyacrylamide, or PAM, (one pound per 800 feet of furrow) in the irrigation water retarded decline of infiltration rate and increased depth of water penetration during several subsequent irrigations (Cass et al, 1991).

- PAM (polyacrylamide) applied at a rate of 30 pounds per acre in the irrigation water improved infiltration rates by as much as 57% during the first four hours of subsequent irrigations. But it did not increase the final infiltration rate or the total amount of water infiltrated. Application of the same amount as a dry powder to the soil was not effective (Mitchell, 1986).

- Cationic polysaccharide guar derivatives and PAM maintained infiltration rates in a sandy loam, when applied through irrigation water but not when sprayed on soil surface. Only PAM, however, was effective against damage caused by the impact of sprinkler drops and rainfall (Ben-hur et al, 1989).

- LIMA (lignosulfonate reacted with methyl acrylate) applied in the water with a drip irrigation system at a rate of 100 pounds per acre improved crop germination and aggregate stability at three field sites in Israel (Shaviv et al, 1985).

- Polyurea soil conditioner (0.5%) improved the aggregate stability of a one-inch surface layer of silt loam with little organic matter and increased infiltration significantly (Hartmann and De Boodt, 1984).

- HPAN (hydrolyzed polycrylonitril) and VAMA (modified vinyl acetate-maleic acid) increased aggregate size when added to soils at rates of 0.05%. VAMA, however, was more effective than HPAN (Martin, 1953; Sherwood and Engibous, 1953).

Negative Results

- Ammonium laureth sulfate, tested in Iowa, not only did not increase crop yields, but even decreased infiltration rates because additional traffic caused more compaction (Hamlett et al, 1988).

- Material described as an "organic liquid soil conditioner" had "no gross effects" on either biological activity or physical properties of New Zealand soils (Orchard et al, 1987).

- "Super Slurper," the commercial name for a highly polymerized polysaccharide, decreased the crust strength of sandy loam, loamy sand, and clay loam, but it also decreased infiltration rates (Hemyari and Nofziger, 1981; Miller, 1979).

SURFACTANTS

Surfactants lower the surface tension between water and soil particles and thus enhance the ability of water-repellent soil to become wet. They are usually ineffective on normal soil. Although water repellent substances frequently accumulate after wildfires or in lawns and golf greens, they are rarely the cause of slow water penetration on agricultural soils in California.

Research shows that surfactants are effective in improving water penetration only when the problem is clearly due to soil with a poor ability to become wet.

- In a study of the sand and sod of dormant bermuda grass, wetting agents were variously effective in overcoming the inability of sod to become wet (Miyamoto, 1985).
- In a study of five penetrating agents on the market, all proved ineffective in field tests, and three actually inhibited water penetration (Mihail and Alcorn, 1983; Table 4.4).

Table 4.4. The influence of penetrating agents on the penetration of water into soil and sand and on pH (Mihail and Alcorn, 1983).

A. SAND						
Compound	Rate	Average penetration time			Average pH effluent	
		Water (sec)	Penetrant (sec)	% of water	Water	Penetrant
Amway	1:800[a]	22.9	4.6	20.1[b]	6.4	6.7
Spray Adjuvant	1:500	94.3	86.0	91.2	6.0	6.3
"Charge"	6:800[a]	92.0	94.7	102.9	7.8	7.2[d]
	8:800	88.3	89.0	100.8	7.5	7.0[d]
Toximul-S	1:800	86.7	93.7	108.1	6.2	6.2
	3:800	85.0	98.0	115.3[c]	6.9	6.8
	6:800	108.3	117.0	108.0	6.9	6.9
Toximul H-HF	6:800	97.7	118.7	121.5[c]	6.8	6.7
B. SOIL						
Compound	Rate	Average penetration time			Average pH effluent	
		Water (min)	Penetrant (min)	% of water	Water	Penetrant
Amway	1:800[a]	21.1	21.3	100.9	7.4	7.5
Spray Adjuvant	1:500	72.0	77.7	107.9[c]	7.2	7.2
"Charge"	6:800[a]	76.7	51.2	66.8[b]	7.3	7.3
	8:800	42.3	28.0	66.2[b]	7.3	7.3
Toximul-S	1:800	173.3	188.8	108.9	7.4	7.4
	3:800	86.3	112.3	130.1	7.6	7.6
	6:800	45.2	51.5	113.9	7.7	7.7
Toximul H-HF	6:800	313.3	450	143.6[c]	7.2	7.5

[a] Application rate recommended by manufacturer
[b] Penetrant significantly faster than water (P < .05)
[c] Penetrant significantly slower than water (P < .05)
[d] pH measurements significantly different (P < .05)

4.1.2 ORGANIC MATTER MANAGEMENT

Organic matter is that part of the soil that has been produced by living organisms. It includes plant and animal residues in various stages of decomposition, as well as microbial cells and substances produced by organisms living in the soil.

In California, organic matter decomposes rapidly because of high soil temperatures. Fresh organic matter promotes microbial activity and is considered most effective in stabilizing soil structure because of the production of polysaccharides and polyuronides. Consequently, improvement in infiltration requires addition of organic matter annually as part of the overall management system.

Organic matter is the primary stabilizing agent for soil aggregates. Moreover, as shown by the research of De Datta and Hundall (1984), Boyle et al (1989), and Martens and Frankenburger (1992) the soil becomes more porous, the aggregates more stable, and the water infiltration better as the organic matter in the soil increases.

Cultivation increases decomposition. Eventually, organic matter content reaches a constant level. At this level, as research by Joffe in 1955 has shown, cultivation practices usually do not reduce organic matter any further.

When adding organic matter, mixing the animal or plant residue lightly into the soil allows more of the residue to contact the soil. This protects the material and its nutrients from being blown or washed away. It also protects the soil structure at the surface from the impact of water drops or from of flowing water.

Organic residues such as green manures that decompose rapidly improve soil structure more quickly than materials such as barley and rice straw that decompose slowly. Such slowly decomposing materials, however, also have the immediate effect of protecting the soil surfaces from the impact of irrigation water before they decompose.

MANURE

Manure, where available, is helpful in maintaining or improving the organic content of soil. Extensive supplies of manure exist in California. The annual manure production by animals and poultry in confinement is about 9 million tons. However, its low nutrient content and high transportation costs make its use impractical except in fields close to the source.

The nitrogen (3-6%) and salt content (6-10%) of manure also require appropriate management to minimize damage to the environment. The total nitrogen applied (inorganic fertilizer plus manure) should not exceed crop needs. The salts in the manure (100 - 200 pounds per ton) will likely be leached by normal irrigation practices. When large amounts of poultry manure are applied to clay, silty clay, and clay loam soils, deep tillage plus a large irrigation may be required to lower salinity levels in the root zone.

Research suggests that consistently adding manure improves water infiltration.

- In an eight-year study at the Imperial Valley Conservation Research Center in Brawley, California, infiltration rates were directly related to the organic content of a silty clay soil. With cattle manure added each year at rates of 20 tons per acre or higher, infiltration rates improved during the growing season but not after the harvest. With manure added only once at 150 tons per acre, organic content declined and infiltration rates slowed one year after the addition (Meek et al, 1982).
- Poultry manure, raw or composted, increased infiltration rates in a vineyard with Ramona sandy loam. Manure was applied in November for three successive years at an application rate of 2 and 4 tons per acre in 1.7-foot wide bands on each side of the vine row. It was tilled into the upper 4 inches of soil (Bhangoo et al, 1988).
- Martens and Frankenberger (1992) improved infiltration rates of an Arlington sandy loam by incorporating poultry manure, sewage sludge, barley straw, and alfalfa. For increasing cumulative water infiltration, the additions of barley straw, alfalfa, and sewage sludge were significantly more effective than adding only poultry manure or not treating at all.

COVER CROPS AND SURFACE MULCHES

Covering the surface with either living plants or mulch protects soil structure from slaking by water flow or water drop impact. The roots of cover crops help to aggregate the soil, and the decomposition of plant residues aids in maintaining soil structure (Figure 4.5). Miller et al (1989), in a bulletin entitled Cover Crops for California Agriculture, list benefits as lower soil temperatures, fewer weeds, and greater organic matter content in the soil. This bulletin should be read if you are considering growing cover crops.

Figure 4.5. A winter cover crop prevents structural crust formation, reduces erosion, and adds organic matter to the soil. Photo credit, Bill Peacock.

There are some disadvantages to maintaining a cover crop. First, it requires the same management as harvested crops. This management involves extra costs for meeting the cover crop's water and nutritional needs, as well as costs for changing the timing of farm operations to accommodate the cover crop. Second, the cover crop can harbor insects or diseases, and third, crop residues can interfere with harvesting nut crops.

Sowing an annual cover crop in the fall, followed by cultivation the following spring or summer, has been used to minimize these disadvantages. Wheat, barley, or rye provide a luxuriant cover during the winter and spring. The crop cover is either turned under while green or clipped once or twice and then cultivated. The latter practice is preferable, particularly if the clipping is high and cultivation is done after the straw has turned yellow to make a rough trashy surface.

To be effective, the cover crop must grow dense enough to cover the ground. Total ground cover is the most important factor in achieving good final infiltration rates, according to a 1987 study of watersheds in New Mexico (Wood et al, 1987).

Research on cover crops indicates that they improve soil conditions and water infiltration generally, but they do not improve cash crop yields.

- In an almond orchard, the water infiltration characteristics of four cover crop management practices were measured four years after the practices were started. The treatments were resident vegetation (weeds), salinas strawberry clover, brome grass, and bare soil where herbicides were used throughout the year to prevent cover crop growth. Infiltrated water after

120 minutes and steady state infiltration rate were significantly higher for the cover crop treatments than for the bare soil. Differences were greatest toward the end of the irrigation season (Prichard et al. 1989).

- In a seven-year study of a South African vineyard, permanent cover crop plus deep cultivation improved infiltration rates, but significantly decreased yields due to competition for nitrogen and moisture. Clean cultivation produced the slowest water infiltration but the highest yields (Saayman and Huyssteen, 1983).

- Common vetch, a winter legume cover crop, grown in conjunction with a summer cotton crop resulted in no change in soil bulk density but improved infiltration rates (Touchton et al, 1984).

- Brome grass cover crop, whether allowed to grow or killed with herbicide, improved plant-water relations for vines under furrow irrigation but did not increase plant yield (Grimes and Goldhamer, 1990).

- Compared to conventional systems, a killed turf system improved water infiltration, increasing aggregate stability and the number of macropores. In addition, both the yield and growth of peach trees increased due to the improved soil water content (Welker and Glenn, 1988).

SLIT OR VERTICAL MULCHING

Slit or vertical mulching is an effective technique to improve water infiltration, but it requires special equipment and mulch. With this technique, a slit is cut into the soil and coarse organic material is placed into the slit so that it sticks out of the soil surface. These slits provide pathways for rapid water movement.

Research on slit or vertical mulching indicates that it has promise. Practical experience with it, however, is limited.

- In a study of a vineyard under drip irrigation, vertical mulching improved the yield and sugar content but not berry weight. It also reduced evaporation and weed growth, and it improved water infiltration enough to permit weekly instead of daily surface and subsurface irrigation (Biggar and Grimes, 1990).

- In an Australian study of a variation of the slotting technique, 1.8 tons per acre of gypsum was mixed in slits 18-inch deep, 4 inches wide, and 4 feet apart. The emergence number, height, number of tillers and wheat yield were all higher in the treated plots compared to the control plots (Hall, 1990).

- Unger and Stewart (1983) reviewed results of vertical mulching in the West.

- Redinger et al (1984) studied the effects of slot width, depth, and spacing on infiltration rates.

SOIL ORGANISMS (EARTHWORMS)

Managing the number and activity of soil organisms such as earthworms is not a common practice in the United States. Yet, earthworms and other soil fauna are responsible for creating many of the vertical macropores that allow water to move rapidly (Kemper et al, 1987). Satchell (1967) estimated that up to two-thirds of the air-filled pore space in soils may be earthworm burrows. Thus, maintaining soil conditions favorable to worm survival is a good way to improve water infiltration.

To create a soil environment favorable to worms and other soil organisms:

- Maintain abundant organic matter, moderate soil temperatures, and sufficient water.
- Maintain soil fertility, so that high crop yields return abundant residues to the soil.
- Reduce tillage. Intense soil tillage and earthworm activity are not compatible (Gantzer and Blake, 1978).

Research on soil organisms shows that their abundance improves water infiltration.

- Several studies have shown that earthworms improve water movement by increasing the number of pores in the soil (Aina, 1984; Bouma et al, 1982; Trout and Johnson, 1989).
- In a study of soil in laboratory pots, earthworms improved aggregate stability and infiltration rates in soil containing crop residues (Kladivko et al, 1986).

4.1.3 TILLAGE

Shallow tillage is effective in reducing problems of slow water penetration caused by either crusts or compaction. But it also increases compaction, requiring deep tillage from time to time.

FOR CRUSTS

Shallow tillage increases infiltration by roughing up the soil surface. It breaks up both depositional and structural crusts. It also improves infiltration in clay soils. Since the effect of tillage is only temporary, it must be repeated from time to time.

In deciding to use tillage to solve a water infiltration problem caused by crusts, consider the following advice:

- Till before irrigation when the soil is dry.
- Use implements that do not smear or powder the soil. Pulverized soil leads to crust formation. Chisels are better than disks.
- Weigh carefully the benefits and drawbacks of repeated tillage. While it is effective in breaking up crusts and removing weeds, it also creates a tillage or plow pan. This tillage pan reduces infiltration because it has high density and low permeability.

Research shows that shallow tillage temporarily improves problems of slow water penetration caused by crusts.

- In a study of depositional crusts, light tillage temporarily produced much more water infiltration than did cover crops on uncultivated plots (Moore et al, 1989).
- A study on structural crusts in sandy soils found that shallow tillage dramatically improved both infiltration and crop emergence. Since rainfall and irrigation reformed the crusts, the improvement was temporary (Rawitz et al, 1986).

FOR COMPACTION

Deep tillage or subsoiling can loosen compaction caused by traffic or cultivation. It also can loosen naturally dense clay soils and disrupt both structural and depositional crusts (Figure 4.6).

Figure 4.6. These ripper shanks are about 3 feet long and if fully inserted into the soil, will reduce compaction to about 1.5 feet. Photo credit, W. E. Wildman.

In California, deep tillage after harvest of field crops is common. A major benefit is that a large amount of water will penetrate the ground during the first irrigation. This assures that the soils are wet throughout the root zone and that leaching of salts occurs at least during the first irrigation. The disadvantage is that large irrigations generate excess drainage. In some areas of California there is no environmentally acceptable place to dispose of the drainage water.

In California, chiseling to 12-20 inches and ripping to 25-30 inches is the normal practice. The relief, however, is temporary because:

- Tillage after chiseling or ripping to prepare the field for cropping will cause soil compaction.

- The first irrigation after chiseling or ripping will also cause compaction because wet soils have little strength. After the soil becomes wet, the soil will tend to reconsolidate because of its own weight.

- Any additional tillage will tend to cause additional compaction.

When tilling for compaction, chisel or rip 50% deeper than the lower boundary, and space shanks at 80% of depth. For example, if compaction extends down to 16 inches, chisel or rip to 24 inches, and space shanks 19 inches apart.

Orchards and vineyards, where there is no tillage but nonetheless traffic for maintenance and harvest, acquire a traffic pan or compacted layer that extends to the surface. In this case, ripping may be the only alternative to improve water penetration.

When ripping in orchards and vineyards, there are three concerns:

1- Use shanks that will penetrate 16 to 24 inches, depending on the depth of compacted soil, and space shanks at 80% of depth as when tilling for compaction. Six or seven shanks will rip about half the space between trees.

2- To avoid excessive root pruning, rip only every other row middle in any one year, leaving the remaining middles to be ripped a year or two later.

3- Rip only when the soil is dry.

Research suggests that tilling to reduce compaction improves water infiltration only temporarily. The search for new tillage implements continues.

- In a study of tillage and infiltration rates, improved infiltration produced in the fall by chisel tillage did not remain until mid-winter. Similarly, increased infiltration attributed to reduced tillage at planting time did not remain at the end of the growing season (Rumsey et al, 1990).
- In an Australian study, improvements from tillage were short lived for "hard setting" soils, those prone to crusting and structural collapse on wetting (Mead and Chan, 1988).
- In a study of corn and potatoes in the state of Washington, subsoiling was "relatively unimportant" as long as irrigation was adequate (Ibrahim and Miller, 1989).
- In long-term studies of almonds in California, poor water penetration in untilled soil reduced almond yields while moderate cultivation did not reduce yields (Schlesselman et al, 1986).
- In a study of clay soils in Texas, annual chiseling improved cotton lint yields, increased water infiltration in the seed bed, and decreased soil bulk density (Heilman, 1988).
- In a study of Pullman clay loam in the Southern Great Plains, chiseling after the harvest, when the soil was dry, increased infiltration only for one irrigation (Jensen and Sletten, 1965).
- A new implement, the paraplow, loosens 10 to 12 inches of the surface without mixing or inverting the soil (Pidgeon, 1983). In one study it created macropores that remained over the winter (Pikul, et al, 1988).

4.2 Subsurface Problems

Natural layers such as stratification, hardpan, and claypan that limit either deep water penetration or root growth may be permanently changed by slip plowing or ripping. Slip plows, deep moldboard plows, or trenching machines are used to mix layers of stratified soils with different textures and to break up soils with clay or hardpan. Ripping shanks are used to break through cemented hardpan to reach permeable soil underneath.

Figure 4.7. Deep tillage with this slip plow can significantly improve water penetration through stratified soils and soils with claypans and hardpans. Photo credit, W. E. Wildman.

In the subsoil there two kinds of dense layers that affect water penetration: cemented and non-cemented layers. Common examples of cemented layers are silica cemented layers (duripan) and calcium carbonate cemented layers (caliche or petrocalcic horizons). In California iron and aluminum also occasionally produce cemented layers. Common examples of layers that are not cemented include fragipan and claypan. Fragipan is extremely hard but fragile when dry. Claypan is a subsurface layer with high clay content that lies beneath soil with less clay content.

In addition to the following material, you should read Identification and Evaluation of Soils by E. L. Begg and Site Preparation and Correction of Soil Problems by W. E. Wildman in Walnut Orchard Management, 1985, DANR Special Publication 21410 edited by D. E. Ramos.

4.2.1 BREAKING CEMENTED LAYERS

Deep (3 to 6 feet) tillage or ripping can break up cemented layers permanently. As an additional benefit, the trace of the ripper leaves dry cracks at the soil surface. While open, these cracks become pathways for rapid water infiltration (Figure 4.8).

Figure 4.8. Deep ripping to a depth of 6 feet disrupts the upper 3 feet of soil.

Ripping requires pulling a shank through the soil to a depth of four to six feet. To get enough pulling power, it is often necessary to use tandem tractors. This procedure is impractical for orchards and vineyards except when they are being established or when the old crops are being replaced.

Ripping produces permanent improvement if the hardpan is thin enough and shallow enough for ripping to shatter it completely and to break into the non-cemented layers below. If the hardpan is too thick to penetrate, water from excessive rainfall or irrigation may pond in the ripper channel and suffocate any roots that have grown into this zone. Thus, careful evaluation of the depth and thickness of the hardpan is essential before a ripping project is begun. If thoroughly done, ripping is generally a one-time operation. Unlike shallow tillage, its beneficial effects are usually permanent.

4.2.2 MIXING CLAY LAYERS AND STRATIFIED SOILS

Clay layers and stratification require physical mixing of the less permeable layers with the surrounding soil. Simple ripping will not solve the problem permanently. Thorough mixing to give the soil a more uniform texture is the key. With clay layers mixing brings more clay to the surface and promotes surface cracking that enhances infiltration. This mixing can be achieved by slip and moldboard plows, trenchers, and backhoes.

The proper solution for stratification and claypan depends on the nature of the problem and economics. If the layer is shallow, deep plowing or disking may work. If the layer is deep, slip or very deep plowing must be used.

Slip plowing between rows after a tree crop is established is occasionally a good practice. While not nearly as efficient as slip plowing before planting, it can deepen the root zone. With mature trees or vines, slip plow only alternate middles in any one year, leaving the remaining middles to be slip plowed a year or two later.

Mixing of soil profiles is most effective when the soil is dry because dry soil shatters and mixes more thoroughly. Wildman (1981, 1984) recommends a soil water content of 10% for clay, 5% for loam, and 2.5% for sand.

TOOL CHOICE

The tool most frequently used is the slip plow (Figure 4.7). Pulled at an angle through the soil, the slip plow lifts and mixes as it passes through the soil profile. It is especially effective when trees or vines are planted in the plowed area.

In experiments with almonds in soil with claypan, 5-foot-deep ripping in the tree row with two ripper channels between rows resulted in significant improvement compared with the control orchard. Slip plowing increased the average root depth and yield, while deep ripping at 4-foot centers, followed by moldboard plowing 3 feet deep, produced the deepest root zone, largest trunk circumference, and highest yield. See Table 4.5.

Table 4.5. Almond yield, trunk circumference, and root count response to mixing claypan soil by three methods (Wildman, 1985).

Tillage method	Yield[2] lb/A	Trunk circumference[1] inches	Root count[2] per 3 cubic feet
None	1009	14.8	78
Ripper	1120	16.6	94
Slip plow	1185	16.7	118
Moldboard Plow	1433	17.0	175

[1] Fourth leaf. [2] Eighth leaf.

An alternative to deep ripping or slip plowing in preparing soils for orchards or vineyards is to dig through the restricting subsoil layers at each future tree location with a backhoe.

Backhoes offer these advantages:

- They can dig much deeper, if necessary, to get through deep layers.
- They mix soil layers more thoroughly.
- They work on small areas.
- Their pits provide access for fumigation.

Backhoes have these disadvantages:

- The "pot effect" sometimes restricts root growth to the volume of the backhoe pit.
- They are expensive.

COSTS

The cost of deep tillage depends on the method used. Table 4.6 lists the time required for several tools to till one acre deeply. The cost for an operation can be estimated by multiplying the hours per acre by your estimates of equipment and labor costs.

Table 4.6. Approximate time needed for ripper, slip plow, moldboard plow, trencher, and backhoe to till one acre of land for orchard planting (Fulton, 1990, personal communication).

Method	Soil depth ft.	Time needed hours/A
Ripper	4.5	2
Ripper	6.0	2
Slip plow	4 to 6	1
Moldboard plow	4	1.3
Trencher[1]	3.5 (w) x 4.0 (d)	1.4 to 2.5
Backhoe[2]	4 (w) x 4 (l) x 6 (d)	5
Backhoe[3]	4 (w) x 4 (l) x 6 (d)	9.5

[1] Trenching costs assume 3.5 x 4 foot trench down the intended tree row.
[2] Assumes a 17 x 22 foot tree spacing.
[3] Assumes a 12 x 24 foot tree spacing.

Research shows that deep tillage improves infiltration slowed by clay layers and stratification. Where stratification or hardpan is not the source of the problem, however, improvement is sometimes temporary due to compaction.

- In a study of Wyman soil in a prune orchard, deep tillage was simulated by excavating two 20-foot trenches 2 feet wide and 5 feet deep. Trenching increased infiltration rates and the total infiltrated water for only the first irrigation. Soil settling upon wetting during the first irrigation and persistent traffic destroyed the effect (Singer et al, 1984).

- In a study of Pullman soil, deep moldboard plowing, unlike conventional tilling, mixed high clay layers with less clayey soil enough to improve infiltration. In some plots infiltration declined because of compaction caused by harvesting equipment, but the improved rate returned after normal tillage (Schneider and Mathers, 1970).

- In a study of loamy textured soils in Australia, deep moldboard plowing (20 to 24 inches) broke up the hard-setting surface layer and improved wheat yields. Mixing the clay-rich subsoil with the surface promotes cracking on the surface. The improvement, however, did not last beyond the second year unless deep plowing was combined with gypsum applications and crop residue management (Hall, 1990).

4.3 Changing Irrigation Systems

Changing the irrigation system, or the crop (section 2.4) is usually the last resort because of cost and the new management techniques involved. Maybe you should reconsider other options first.

Section 2.1 emphasizes proper management of the existing irrigation system to correct, or at least minimize, the adverse effects of water penetration problems. Starting the irrigation season with a soil profile full of stored water, proper irrigation timing, and control of applied water to prevent excessive ponding are all options which would not require changing the irrigation system.

Sections 4.1 and 4.2 discuss remedial steps to improve water infiltration into soils. Remediation strategies for surface problems include changing water quality with chemical amendments, growing cover crops to increase organic matter, and tillage. Strategies for subsurface problems include deep tillage to break cemented layers or to mix stratified soil layers.

In this section, 4.3, we describe the general characteristics of different irrigation systems. Specific engineering criteria and specifications are beyond the scope of this manual. Several engineers listed in the resource directory can provide such information. Sales representatives for sprinkler and drip irrigation equipment are also sources of information. U. C. Publication 21454, Irrigation Scheduling: A Guide for Efficient On-Farm Water Management, contains a section entitled Irrigation Effectiveness (pp 39-44), which discusses factors affecting performance of surface, sprinkler, and drip irrigation systems. Another reference is Kruse et al (1990).

4.3.1 BORDER AND FURROW IRRIGATION

These irrigation methods are the least expensive and oldest, but they provide the least control over the amount of applied water and where it infiltrates. Infiltration rates are high initially and than decline with time. These rates are higher on freshly tilled soils than on soils which have have not been tilled. Uniformity depends on the time the water remains on the soil surface and on infiltration variability across the field. On soils with water penetration problems, crops are often subjected to long periods of water ponding, poor aeration, and inadequate water content in the subsoil. Tillage, vegetation management, and chemical amendments applied to the soil or the water can improve infiltration.

4.3.2 SPRINKLER IRRIGATION

Historically, hand-move sprinklers have been used most frequently to replace border and furrow irrigation systems. These systems provide complete aerial coverage at a cost ranging from $40 to $80 per acre. Individual sprinklers deliver from 2 to 3.5 gallons per minute: application rates range from 0.15 to 0.3 inches per hour, depending on sprinkler spacing, nozzle size, and water pressure. Most soils with water penetration problems have basic infiltration rates less than 0.10 inches per hour after 2 to 4 hours of sprinkler irrigation. Runoff, inadequate water penetration into subsoils, and standing water often occur as a result.

Mini-sprinklers are a more recent irrigation system alternative. Costs can approach $1300 per acre. They are only used in tree and vine crops because the risers are too short for mature row-crop canopies. Individual sprinklers deliver about 1.0 gallon per minute. Typical application rates are 0.07 to 0.10 inches per hour. These low rates are useful on soils with slow water penetration problems.

Micro-sprinklers deliver 7 to 9 gallons per hour (0.1 to 0.15 gallons per minute). Like mini-sprinklers, they are only used in tree and vine crops. Costs range from $600 to $900 per acre. They are less expensive than mini-sprinklers because micro-sprinklers do not have any moving parts. Common application rates are 0.08 to 0.1 inches per hour though only 40 to 60 percent coverage is achievable. Consequently, the application rates within the wetted perimeter are greater than for mini-sprinklers.

Small frequent irrigations are possible with sprinkler systems, particularly when permanently installed. Consequently, problems with water ponding and runoff are more easily managed than with border and furrow irrigation systems. The effects of soil variability are also less significant, particularly if ponding doesn't occur. Finally, the applied water can be easily and accurately measured with meters.

4.3.3 DRIP IRRIGATION

Surface or subsurface drip irrigation can be used to irrigate row, vine, and tree crops. Application rates range from 0.02 to 0.15 inches per hour. Water is distributed through plastic tubing or tape and emitted through drippers, tricklers, or bubblers. Water infiltrates the soil at or very near the point where it is applied. Costs range from $400 to $1300 per acre, depending on the selection of drip products and system design.

Drip tapes constructed from thin-wall (4 to 25 mil) polyethylene can have emmitters spaced from 2 to 24 inches apart along the tape. Discharge rates range from 0.25 to 1.5 gallons per minute per 100 feet of tape. The functional life of the tape ranges from 1 to about 5 years. Costs range from 1 to 6 cents per foot, depending on the wall thickness.

Drip tubing with inline emitters or emitters welded to the inner wall of the tube are alternatives to tapes. Since drip tubes have thicker walls than drip tapes, they can be buried deeper in the soil. Emitter spacing of about 3 feet is common, with hourly discharge rates ranging from 0.15 to 0.3 gallons per foot. Functional life exceeding 10 years is possible. Costs range from 8 to 20 cents per foot.

Drip irrigation systems can apply water at lower rates than sprinkler systems. Even so, water infiltration rates can be too low for surface drip irrigation systems. As can be seen in the photo, Fig. 4.8, surface ponding can occur around the emitter. If ponding occurs, the underlying soil can become dry, and the root zone can be restricted to the soil immediately beneath the ponded water. Poor crop growth and yields have been encountered with surface drip systems installed on soils with low infiltration rates.

Figure 4.9. Surface ponding also occurs with drip irrigation on problem soils. Photo credit, Bill Peacock.

Several farmers have overcome problems with low infiltration rates by using subsurface drip irrigation. Water is placed directly in the root zone and root growth adjusts to soil water content which decreases with distance from the emitter. The dry soil surface lessens the humidity below the crop canopy and reduces problems due to molds, mildews, and weeds.

Subsurface drip and surface drip requires attention to irrigation management and chemigation to avoid plugging from mineral precipitates, biological growth, and root intrusion (Phene et al, 1988; Schwankl and Prichard, 1990)

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