

**Artificial Recharge for Conjunctive Use in Irrigation:
The San Joaquin Valley, California**

by

Virat Chatdarong

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Chulalongkorn University

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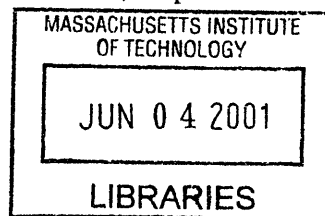
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Author.....
Department of Civil and Environmental Engineering
May 11, 2001

Certified by.....
Dennis B. McLaughlin
H.M. King Bhumibol Professor of Water Resource Management
Thesis Supervisor

Accepted by.....
Oral Buyukozturk
Chairman, Department Committee on Graduate Students



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Abstract

One classical solution for dealing with surface water fluctuation is to construct a surface reservoir. However, because a surface reservoir requires too much land and has high negative impact on the environment, the use of a natural aquifer as a subsurface reservoir is proposed. In this solution, restoration of water to an aquifer requires an artificial recharge method. It is deduced that for irrigation purposes, a direct surface recharge is the most appropriate method to use because of its low cost of construction, operation and maintenance.

To store water for agriculture, the capacity to recharge water within a limited time is the most important characteristic determining the feasibility of artificial recharge. Regarding a direct surface method, this capability is mainly governed by soil properties, depth to groundwater table, and spacing between two adjacent recharge areas. Under proper conditions, sufficient amounts of recharge water can store for agricultural purposes within a region.

This study shows that total costs to construct, operate and maintain artificial recharge facilities are relatively low compared to the benefits that are expected from the recharge project. This implies that an artificial recharge scheme is a practical way to restore water to an aquifer, and use it in conjunction with surface water for irrigation.

Thesis Supervisor: Dennis B. McLaughlin

Title: H.M. King Bhumibol Professor of Water Resource Management

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Contents

LIST OF FIGURES	6
LIST OF TABLES	7
CHAPTER 1 INTRODUCTION	8
1.1 OBJECTIVES AND RESEARCH ISSUES	8
1.2 CONJUNCTIVE USE AND AQUIFER AS A VIEW OF SUBSURFACE STORAGE	9
1.3 STUDY AREA: THE SAN JOAQUIN VALLEY.....	11
1.3.1 <i>General Characteristic of the San Joaquin Valley</i>	12
1.3.2 <i>Conjunctive Use in the San Joaquin Valley</i>	13
CHAPTER 2 ARTIFICIAL RECHARGE	15
2.1 GROUNDWATER RECHARGE	15
2.1.1 <i>Natural Recharge</i>	15
2.1.2 <i>Artificial Recharge</i>	16
2.2 METHODS OF ARTIFICIAL RECHARGE.....	16
2.2.1 <i>Direct Surface Methods</i>	17
2.2.2 <i>Direct Subsurface Methods</i>	17
2.2.3 <i>Combination Surface-Subsurface Methods</i>	18
2.2.4 <i>Indirect Methods</i>	18
2.3 FACTORS AFFECTING RECHARGE METHODS	21
2.3.1 <i>Hydro-Geologic Characteristics</i>	21
2.3.2 <i>Topography and Stream Flow</i>	22
2.3.3 <i>Water Supply Characteristics</i>	22
2.3.4 <i>Miscellaneous Factors</i>	23
CHAPTER 3 DESIGN OF A DIRECT SURFACE RECHARGE FACILITY	24
3.1 ARTIFICIAL RECHARGE DESIGN ISSUES.....	24
3.2 RECHARGE ANALYSIS	24
3.2.1 <i>The Simulation Model</i>	25
3.2.2 <i>Simulation Assumptions</i>	26
3.3 GROUNDWATER RECHARGE BEHAVIOR	27
3.3.1 <i>Behaviors of Unsaturated Flow</i>	27
3.3.2 <i>Behavior of Saturated Flow</i>	31
3.4 EFFECTS OF SOIL CHARACTERISTICS, DEPTH TO GROUNDWATER, AND SPACING	34
3.4.1 <i>Effects of Soil Characteristics</i>	34
3.4.2 <i>Effect of Depth to Groundwater Table</i>	36
3.4.3 <i>Effect of Spacing Between Adjacent Recharges</i>	38
3.5 WATER RECOVERY	40
3.6 ARTIFICIAL RECHARGE MAINTENANCE	40
3.7 CONCLUSION FOR GROUNDWATER RECHARGE ANALYSIS	41

CHAPTER 4 SITE SELECTION AND ECONOMIC ANALYSIS	43
4.1 ARTIFICIAL RECHARGE SITE SELECTION	43
4.1.1 ArcView GIS	43
4.1.2 Data for Artificial Recharge Site Selection	44
4.1.3 Proposed Artificial Recharge Site in the San Joaquin Valley Area	46
4.2 ECONOMIC ANALYSIS AND FEASIBILITY OF THE PROJECT	49
4.2.1 Economic Analysis Scheme	49
4.2.2 Estimation of the Costs from Artificial Recharge	49
4.2.3 Estimation of the Benefits from Artificial Recharge	51
4.2.4 Feasibility of the Project	52
CHAPTER 5 CONCLUSIONS	53
5.1 SUMMARY OF PROJECT	53
5.1.1 Artificial Recharge Methods for Conjunctive Use in Irrigation	53
5.1.2 Important Factors in Artificial Recharge	54
5.1.3 Ability to Pump Stored Water for Irrigation	54
5.1.4 Feasibility of the Artificial Recharge Project	55
5.2 RECOMMENDATIONS FOR FUTURE RESEARCH	56
5.2.1 Radial Configuration Artificial Recharge	56
5.2.2 Actual Recharge Behaviors vs. Simulation Behaviors	56
5.2.3 Detailed Simulation and Economic Analysis	56
APPENDIX A ARTIFICIAL RECHARGE SIMULATION MODELS	57
A.1 SYMMETRICAL MODEL RESULTS	57
A.2 ECONOMIC ANALYSIS: COSTS	57
A.3 ECONOMIC ANALYSIS: BENEFITS	58
REFERENCES	60

List of Figures

Figure 1-1: Map and Groundwater Basins in the San Joaquin Valley	11
Figure 1-2: Cross-Section of San Joaquin Valley Strata of Tulare and Kings County	12
Figure 1-3: Land Subsidence Due to Overdraft in the San Joaquin Valley (Near Mendota) (Sources: U.S. Geology Survey)	13
Figure 3-1: Recharge Water Simulation Model in Hydrus 2-D	25
Figure 3-2: Infiltration Rate from Green-Amp Equation	29
Figure 3-3: Groundwater Mound During Recharge (Asano, 1985).....	31
Figure 3-4: Artificial Recharge Simulation of Sandy Soil by Hydrus 2D	33
Figure 3-5: Effect of Soil Type to Recharge Rate and Cumulative Recharge Water	36
Figure 3-6: Effect of Depth to Groundwater on Recharge Rate and Cumulative Recharge	37
Figure 3-7 Effect of Spacing Between Two Adjacent Recharge Site	39
Figure 4-1: Example of Groundwater Depth and Surface Elevation Data Using ArcView GIS	45
Figure 4-2: Proposed Artificial Recharge Site by ArcView GIS	46
Figure A-1: Recharge Rate and Cumulative Recharge Rate of Proposed Artificial Recharge Sites	57

List of Tables

Table 1-1: Advantages and Disadvantages of Subsurface Reservoir Compared to Surface Water Storage.....	10
Table 2-1: Techniques Used in Direct Surface Recharge Methods	19
Table 2-2: Techniques Used in Direct Subsurface Recharge Methods.....	20
Table 3-1: Green-Ampt Infiltration Parameters for Various Soil Classes.	28
Table 3-2: Representative Artificial Recharge Rates.....	30
Table 3-3: Characteristic of Soil Types Used in the Recharge Simulation.....	35
Table 4-1: Details of Proposed Artificial Recharge Site for the San Joaquin Valley, California.....	48
Table 4-2: Approximate Annual Cost of Artificial Recharge Project.....	51
Table 4-3: Potential Crop Revenues from Artificial Recharge Project.....	52
Table A-1: Land Acquisition Cost in the Great Valley, California	57
Table A-2: Energy Cost to Required to Lift One Acre-foot of Water One Foot of Elevation.....	58
Table A-3: Crop Water Needs and Sensitivity to Drought	58
Table A-4: Average Crop Yields for Difference Crop Types (Ton/Acre).....	59

Chapter 1

Introduction

For many centuries, dams and surface reservoirs have been constructed to deal with fluctuations of surface water. The primary purpose of these gigantic constructions is to store and provide adequate amounts of water. With higher technologies and research studies, we currently have more options to deal with variability of water. One possible alternative is to recharge an aquifer and use it as groundwater storage.

1.1 Objectives and Research Issues

Our interest in artificial recharge for conjunctive use emerges from its advantages over surface reservoirs. Artificial recharge creates smaller surface interference and has fewer effects on the environment. We would like to study the possibility of applying this concept to store water for irrigation. Thus, we need to understand more about water recharge behavior, and the feasibility of artificial recharge.

The main research issues addressed in this study are:

- What are the suitable artificial recharge methods for irrigation purposes?
- Which are the important recharge characteristics and what affect these characteristics?
- Where should we construct artificial recharge facilities in the study area?
- Is the artificial recharge project economically feasible and practical to use?

1.2 Conjunctive Use and Aquifer as a View of Subsurface Storage

Conjunctive use of surface and groundwater may be defined as any scheme that capitalizes on the interaction of surface and groundwater to achieve a greater beneficial use than if the interaction were ignored.

As population increases, water demands also increase dramatically. As a consequence, water stored in surface reservoirs becomes inadequate. Moreover, due to higher land values and concerns for environmental issues, the potential to construct dams or any large surface reservoirs to provide sufficient water is widely opposed. This leads to a combined use of surface and groundwater together, known as conjunctive use.

Since the 1900s when humans first developed turbine engines and applied them to withdraw water from subsurface storage, enormous amounts of water have been consumed. The rate of pumping has been far beyond the capability of nature to refill those groundwater storages. As a result, groundwater has quickly dissipated, and many economic and environmental issues have become apparent. These facts inspire scientists to find an alternative way to increase the natural recharge that refill these groundwater storages.

Study of man-made infiltration, called artificial recharge, has been introduced to balance demand and supply. In addition, it allows the use of natural groundwater aquifers as subsurface reservoirs to store excess water and then provide it in demanding periods with little or no impact on groundwater depletion.

The judgment to consider the existing natural aquifers as reservoirs depends on optimizing the tradeoffs between advantages and disadvantages of the subsurface reservoir method. Typical examples are shown in Table 1-1.

**Table 1-1: Advantages and Disadvantages of Subsurface Reservoir
Compared to Surface Water Storage**

Advantages	Disadvantages
1. Subject to little or no evaporation	1. Unable to recover all water
2. Require little or no construction work	2. Have difficulty in removing salts
3. Have Large storage capacity	3. Need well treatment and maintenance to prevent clogging
4. Cause little or no interference to surface land use	
5. Have less risk of contamination	

Because surface and subsurface reservoirs have such different characteristics, in order to address the plan for conjunctive use, it is imperative to understand their characteristics, mechanisms of recharge, as well as parameters that will affect those behaviors.

1.3 Study Area: The San Joaquin Valley

The San Joaquin Valley is located in the southern half of California's Great Central Valley. It is known as California's largest and most productive agricultural area. The San Joaquin valley has an area of about 3.4 million hectares, or 8.5 million acres. This fertile farmland is located between the Sierra Nevada, the Coast Range, the Tehachapi Mountains, and the Delta of the Sacramento and San Joaquin Rivers.

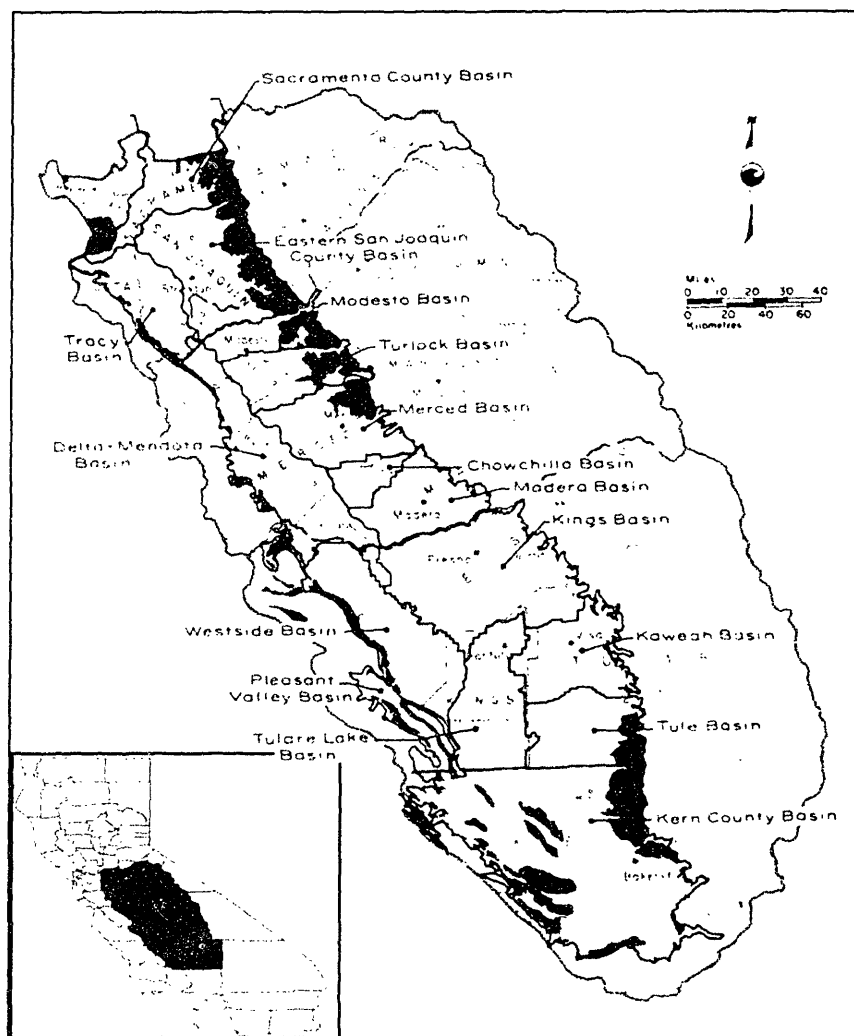


Figure 1-1: Map and Groundwater Basins in the San Joaquin Valley

1.3.1 General Characteristic of the San Joaquin Valley

The typical terrain in the San Joaquin is a flat plain surrounded by mountains. Its floor gradually slopes downward toward the northwest, and dips to the west toward its centerline. The average height of the valley is about at sea level in the flat plain and reaches the level of about 300 feet at the foot of the Tehachapi Mountain.

Major rivers in this area from north to south include the Stanislaus, Tuolumne, Merced, Chowchilla, Fresno, San Joaquin, Kings, Kaweah, Tule, and Kern. These rivers originate in the Sierra Nevada Mountains to the east and flow northwest toward the valley. Annual precipitation in the valley ranges from 100 millimeters in the southern end to about 450 millimeters in the northern end of the valley near the base of the Sierra foothills.

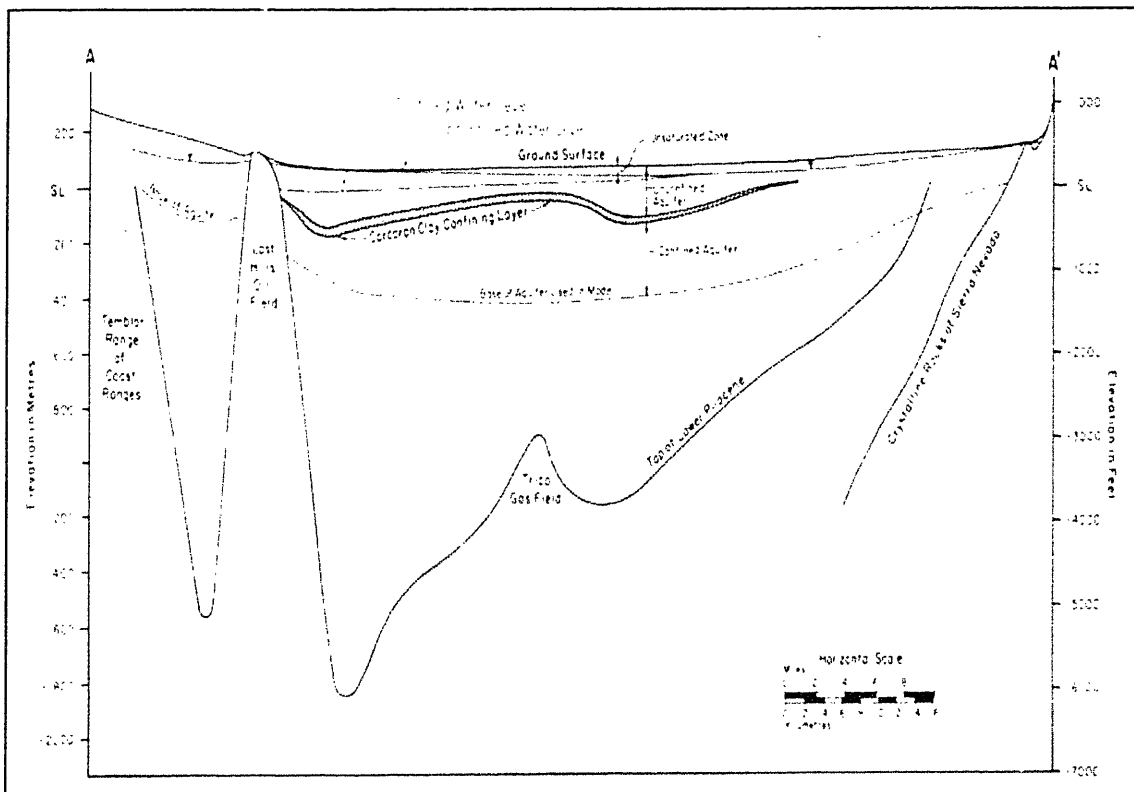


Figure 1-2: Cross-Section of San Joaquin Valley Strata of Tulare and Kings County

There are three main groundwater bodies in the area: an unconfined aquifer, a confined aquifer and a water body in consolidated rocks. The confining layer underlines most of the basin at a depth between 50 to 250 feet extending from the east to the west. The typical range of well yields is about 1000 to 2000 gallon per minute.

1.3.2 Conjunctive Use in the San Joaquin Valley

The San Joaquin Valley has been developed from a semiarid region to the richest agricultural area in the world. About 2 million hectares of the land is used for agricultural purposes. Although the growing season is long and the soil is fertile, rainfall and surface water supply are limited. Therefore, most farmers draw water from the subsurface aquifer to meet the irrigation demand.

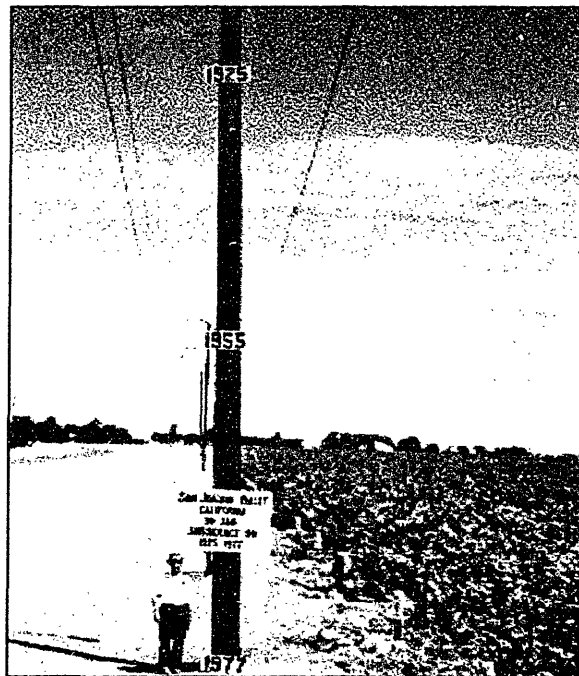


Figure 1-3: Land Subsidence Due to Overdraft in the San Joaquin Valley (Near Mendota)
(Sources: U.S. Geology Survey)

The availability of turbine pumps since the 1920s allows farmers to supply water for their irrigation from subsurface aquifer regardless of surface water. Any land, even located far away from surface water supplies, can grow crops using turbine pumps to withdraw

subsurface water. Groundwater supplies enable agricultural production to expand rapidly and to yield more income to the region. At the same time, a large amount of groundwater is consumed annually which has resulted in drastic declines in groundwater level in many parts of the Valley. A drop in the groundwater level has consequently caused significant increase in the energy cost to pump water for irrigation and brings up many economic and environmental issues, e.g. land subsidence, salt water intrusion.

In response to this problem, the federal government's Central Valley Project (CVP) began delivering water to the Valley in the 1940's, and California's State Water Project (SWP) followed with additional programs. Artificial recharge has been conducted as a method to alleviate groundwater crises and to augment the subsurface aquifer. It has been proved in many projects that artificial recharge schemes are efficient to augment groundwater level.

Even though artificial recharge is practical to use in many areas, more research for a better understanding of groundwater recharge is needed to specify more precise benefits, effects to the environment, and effective strategies for conjunctive use.

Chapter 2

Artificial Recharge

In this chapter we will present the general knowledge about groundwater recharge, e.g. definitions, methods, and important factors that would affect the behavior of recharge. This knowledge will provide more understanding about artificial recharge behaviors that will lead to the simulation model in the next chapter.

2.1 Groundwater Recharge

Groundwater recharge is the process of transferring surface water into a groundwater aquifer. The main purpose is to augment the amount of groundwater availability. Groundwater recharge is classified into 2 broad categories: natural recharge and artificial recharge.

2.1.1 Natural Recharge

Natural groundwater recharge is the process by which recharge occurs without control by human activities. Recharge water may come from several natural sources, such as deep percolation of precipitation, percolation of water through streambeds, or subsurface flow from adjacent aquifers. Commonly, deep percolation of rainfall and seepage of stream water through the ground are the largest sources of natural recharge in most places. Natural recharge varies from place to place depending mainly on soil types and weather conditions.

In many areas, groundwater rapidly declines due to high rate of pumping. Natural recharge alone is not sufficient to refill an aquifer. To deal with this groundwater

depletion, artificial recharge is introduced to augment natural recharge and supply more water to an aquifer.

2.1.2 Artificial Recharge

Artificial recharge is a human-planned activity conducted to increase natural recharge to refill a groundwater aquifer. Even though it is named as 'artificial' recharge, its behaviors still follow the same principal laws that applied to natural recharge. The only difference is that in artificial recharge, people are managing water supply to be at particular location and at particular time. In the broad definition, artificial recharge may be expressed as managed groundwater recharge.

While the primary objective of artificial recharge is to preserve and enhance the availability of groundwater, it can be used for other purposes. Examples of other common objectives are conservation and disposal of floodwater, control of saltwater, storage of water for the pumping cost reduction, and improvement of water quality, etc. It is common for an artificial recharge project to be multi-objective because a multi-objective project is typically more economically feasible than a single-objective project.

2.2 Methods of Artificial Recharge

There are many methods developed for artificial recharge to increase groundwater supplies. In general, they are classified into 4 broad categories. (Oaksford: 1985)

1. Direct surface methods
2. Direct subsurface methods
3. Combination surface-subsurface methods
4. Indirect methods

2.2.1 Direct Surface Methods

Direct surface methods are the simplest, oldest and most widely used method. They have relatively low cost of construction, operation and maintenance. In direct surface methods, water percolates from a surface water supply through the soil to an aquifer. The surface recharge methods have been used in many existing large-scale artificial recharge projects in western countries. From field research, of many factors governing the amount of water recharging an aquifer, the area of recharge and the length of time that water is in contact with soil are the most important factor. (Todd, 1980)

Direct surface methods include flooding, ditch and furrow, basins, stream channel modifications, stream augmentation and over-irrigation technique. Because direct surface methods have relatively low cost of construction, operation and maintenance, it is recommended for recharging groundwater for irrigation purposes. Concepts, limitations and advantages of each direct surface technique are summarized in Table 2-1.

2.2.2 Direct Subsurface Methods

Direct subsurface methods are recharges of groundwater by conveying water directly into aquifers. Generally, direct subsurface methods are used to recharge confined aquifers. Techniques of direct subsurface methods include injection of water into natural openings in the aquifer, pits or shafts, wells, and drainage pipe networks. Concepts, limitations and advantages of each direct surface technique are summarized in Table 2-2.

The obvious advantage of direct subsurface methods is that they require small amounts of surface area and have little or no interferences with surface land use. Moreover water loss to evaporation is significantly less than direct surface methods. However, quality of supply water is a big concern for the subsurface methods. To prevent clogging, the supply water needs to be treated before injecting into the ground, resulting in higher cost of construction, operation and maintenance.

In general, direct subsurface methods are suitable to supply water in urban areas where there are limited spaces and land values are costly. For irrigation areas, where land values are relatively cheap, subsurface method may not be economically feasible.

2.2.3 Combination Surface-Subsurface Methods

Several direct-surface and subsurface methods can be used in conjunction with one another to meet specific recharge needs. Advantages and limitations of each combination technique result from both surface and subsurface techniques mentioned earlier. Examples of the combination methods include subsurface drainage collectors with wells, basins with pits, shafts, or wells, etc.

2.2.4 Indirect Methods

The concept of the indirect method is to allow an increased rate of groundwater withdrawal from an aquifer, without necessarily increasing water in a groundwater aquifer. An example for the indirect method is to increase an allowable pumping rate by locating pumping facilities near a lake or a stream. In this example, the pump will lower the groundwater level, increasing the water infiltration from adjacent surface water supply. Because indirect methods do not necessarily increase groundwater storage, many people do not consider them to be artificial recharge methods.

Table 2-1: Techniques Used in Direct Surface Recharge Methods

Recharge Technique	Concept	Advantage	Limitation
1. Flooding	<ul style="list-style-type: none"> - Spreads water over a large area in a thin film which flows slowly downhill without disturbing the soil 	<ul style="list-style-type: none"> - Has relatively low cost of construction and maintenance 	<ul style="list-style-type: none"> - Requires large surface areas - Subject to large amounts of evaporation
2. Ditch and Furrow System	<ul style="list-style-type: none"> - Recharge water passes through shallow, flat-bottomed ditches or furrows 	<ul style="list-style-type: none"> - Provides the greatest efficiency for high suspended solids recharge water 	<ul style="list-style-type: none"> - Allows small recharge volume with respect to recharge area
3. Basins	<ul style="list-style-type: none"> - Diverts water from a main stream to a single basin or a series of basins 	<ul style="list-style-type: none"> - Allows longer time of recharge - Can store flood water - Can use a series of basins for filtering sediment - Allows efficient use of land 	<ul style="list-style-type: none"> - Has relatively high cost of construction - Need occasional maintenance to prevent surface clogging
4. Stream Modification	<ul style="list-style-type: none"> - Modifies a natural channel to increase infiltration 	<ul style="list-style-type: none"> - Has a relatively low cost of construction - Has little conflict with surface land uses 	<ul style="list-style-type: none"> - Can recharge only seasonally
5. Over-irrigation	<ul style="list-style-type: none"> - Applies water for irrigation during non-growing seasons 	<ul style="list-style-type: none"> - Minimizes cost of construction 	<ul style="list-style-type: none"> - Subject to large amounts of evaporation

Table 2-2: Techniques Used in Direct Subsurface Recharge Methods

Recharge Technique	Concept	Advantage	Limitation
1. Natural Opening	<ul style="list-style-type: none"> - Drains water directly into fracturing or cavernous limestone or soluble rocks 	<ul style="list-style-type: none"> - Has relatively low cost of construction and maintenance 	<ul style="list-style-type: none"> - Requires favorable terrain and geologic conditions
2. Pits and Shafts	<ul style="list-style-type: none"> - Constructs deep pit and shafts penetrating through confined layer and applies recharge to it 	<ul style="list-style-type: none"> - Requires less attention to operate and maintain than well injection - Use of abandoned gravel pits or quarries can reduce the cost of construction 	<ul style="list-style-type: none"> - Cannot be use for deep and thick confining layers - Cannot be redeveloped by pumping - Requires periodic treatment to prevent clogging
3. Wells	<ul style="list-style-type: none"> - Injects water directly into confined aquifers through wells 	<ul style="list-style-type: none"> - Can be used to recharge more than one aquifer simultaneously - Allows the use of subsurface water sources to recharge aquifer - Minimizes the operation area - Has no interference with surface land uses. 	<ul style="list-style-type: none"> - Has high cost of construction, operation and maintenance - Requires high quality of recharge water
4. Drainage Pipe Networks (Reverse Drainage)	<ul style="list-style-type: none"> - Drains water through pipe network which facilitates infiltration into the soil 	<ul style="list-style-type: none"> - Minimizes effect on surface land use 	<ul style="list-style-type: none"> - Has relatively high cost of construction, operation and maintenance - Requires periodic maintenance to prevent clogging

2.3 Factors Affecting Recharge Methods

To determine the best location of a recharge facility and to select suitable recharge strategies, we need to understand factors that affect recharge behavior. This section will provide fundamental concepts for choosing recharge methods. After a suitable recharge method is selected, we will then discuss the factors that affect recharge rate and total recharge water in Chapter 3.

In many cases, the site location cannot be predetermined. The choice of recharge method must be based on recharge objectives and the given conditions. These aspects include hydro-geologic characteristics, topography and stream flow, water supply characteristics, legal aspects, availability of land, land use in adjacent area, and public acceptance.

2.3.1 Hydro-Geologic Characteristics

An appropriate type of recharge method depends mainly on the type of aquifer. Direct surface methods are commonly used for recharging unconfined aquifers, while direct subsurface methods are used for confined aquifers. The appropriate choice also depends on physical, chemical and biological properties of the soil. Other relevant hydro-geologic factors include:

- Permeability of unsaturated soil deposits and depth to ground water determine the allowable infiltration rate for surface applications.
- Permeability, specific yield, thickness of saturated subsurface deposits, position and fluctuation of the water table determine the total water storage capacity.
- Transmissivity and hydraulic gradient determine the rate of groundwater movement away from the recharge area, to or away from the withdrawal area.
- Underground structures and barriers affect transmissivity, hydraulic gradient and direction of groundwater movement.

2.3.2 Topography and Stream Flow

Topography has a great influence on choosing a recharge method, especially when the surface techniques are considered. Recharge by flooding, irrigation, or land treatment requires relatively flat lands. In contrast, basins, canals, and ditches usually follow topographic contours and can be used in relatively steeper areas. For the subsurface techniques, a topographic setting has very small effect. Subsurface techniques provide alternatives where topography is inappropriate for surface recharge techniques.

2.3.3 Water Supply Characteristics

Two important factors in water supply characteristics are quantity and quality of recharge water. When quantity or availability of recharge water is highly variable, surface application methods are more suitable. Basin and pit techniques have the greatest advantages because they can be designed to contain excess flood flow. Shafts and wells have little storage capacity. Thus, they require less fluctuating water supply.

A decision to select a recharge method also depends on the physical, chemical, and biological quality of recharge water. Physical quality refers to types and amounts of suspended solids, the temperature and the amounts of entrained air. If a large number of suspended particles are present in the recharge water, surface techniques are more efficient than subsurface techniques. Unless pretreatment is efficiently designed, subsurface techniques are prone to failure because of clogging. However, the suspended particles may also cause clogging for surface methods; thus, remedial treatments may be needed for surface methods as well. Ditch and furrow methods are recommended for turbid water because the steady flow of water inhibits settling. If basins are used, they should be placed in a series where the first basin acts as a filter for subsequent basins.

For chemical quality, recharge water should be chemically compatible with existing water in the aquifer. Incompatibility of recharge and existing water may lead to chemical reaction that dissolves aquifer material and produces gases, which consequently results in

clogging or improper pH of water. In addition, some toxic substances may be released as a result of chemical reactions.

The final type of water quality is biological quality. It refers to types and concentrations of living organisms. Harmful biological agents such as algae or bacteria and organic wastes may be presented in recharge water. Although surface methods can reduce significant amounts of organic wastes, bacteria and algae by infiltration, these organisms will cause surface clogging that dramatically decrease the infiltration rate. For direct subsurface methods, injections of water with biological agents directly through wells also lead to serious clogging of well screens or aquifer materials, which are costly and very difficult to remedy.

2.3.4 Miscellaneous Factors

Apart from physical factors, social factors also play important roles in select the artificial recharge methods. For many regions, social factors are the primary concern for determining the recharge type. Availability of land, surface land use, public attitudes, and legal aspects are the examples of social factors that need to be considered. On one hand, in urban areas, where land availability is low and access to land is restricted, subsurface recharge methods are commonly preferable to larger scale surface-spreading recharge methods, even though the costs of operating and maintenance are significantly higher. On the other hand, surface recharge methods are suitable for an irrigation area, where land value is relatively low.

From these general ideas about artificial recharge, we conclude that direct surface recharge methods should be used for irrigation purpose in the San Joaquin Valley. After we select the recharge method, we will estimate total amounts of recharge water and study recharge behavior to plan strategies and evaluate the feasibility of the project.

Chapter 3

Design of a Direct Surface Recharge Facility

In this chapter, we will introduce three main issues that we need to consider for designing a direct surface recharge facility. Then we will discuss these issues in detail on how they can affect the sized, location and recharge strategy of the artificial recharge project.

3.1 Artificial Recharge Design Issues

Three main issues in designing an artificial recharge facility are 1) recharge characteristic issue, 2) water recovery issue, and 3) maintenance issue. Our study will focus mainly on the recharge characteristic issue by introducing a 2-D simulation program to illustrate the behavior of recharge water, and to observe the sensitivity to the change various design factors. We will also address some importance of water recovery and maintenance issue in designing an artificial recharge facility at the end of this chapter.

3.2 Recharge Analysis

For the purposes of conjunctive use in irrigation, direct surface methods are selected to recharge groundwater. In this study, the behavior of recharge water from a ditch and furrow technique is illustrated by using the 2-D computer-modeling program.

3.2.1 The Simulation Model

To study recharge behavior, we use a computer-modeling program called Hydrus 2D¹. This program can analyze water flow and solute transport in variably saturated and unsaturated porous media. It uses the finite element method to simulate movement of water, heat and multiple solutes. The program numerically solves the Richards' equation for unsaturated water flow and the Fickian-based advection dispersion equation for heat and solute transport.

For the simulations, we construct two-dimensional models based on an actual infiltration field as shown in Figure 3-1. It illustrates a cross-section perpendicular to a single ditch. We can assume that the modeled region is a box 1 m. thick with imaginary walls of glass at the front and the back. Subsurface water can only flow in the direction perpendicular to the axis of the infiltration ditch. Note that an infiltration rate from the simulation is in the unit of volume per unit length per time (i.e. $\text{m}^3/\text{m}/\text{day}$) instead of volume per unit area per time (i.e. m/s), which is commonly used.

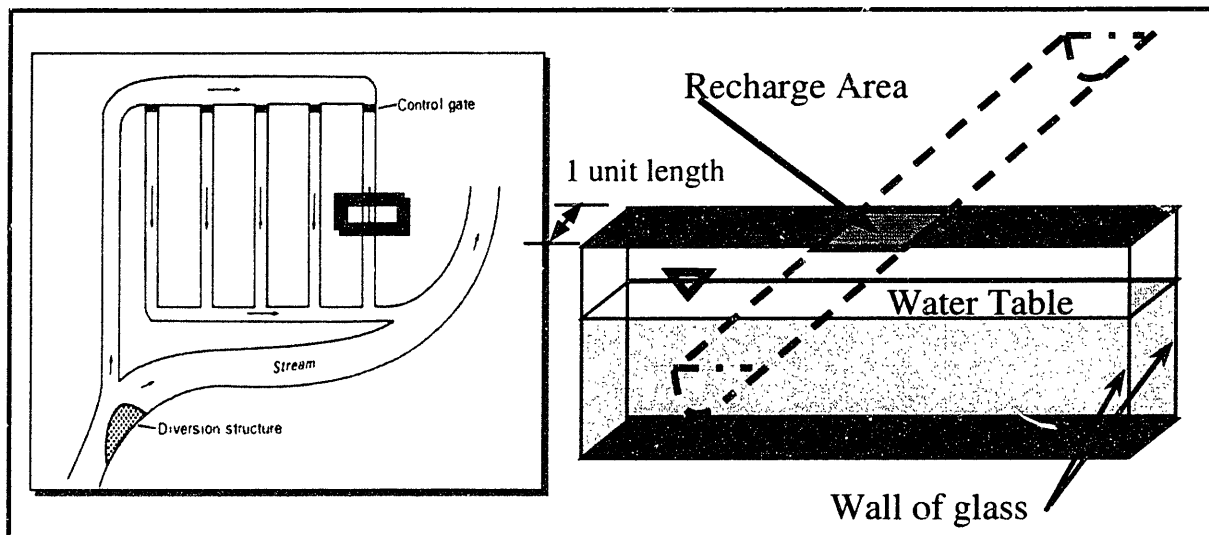


Figure 3-1: Recharge Water Simulation Model in Hydrus 2-D

¹ Developed by U.S. Salinity Laboratory, Agriculture Research Service, U.S. Department of Agriculture, River Side, California. (Version 2.0: April 1999)

3.2.2 Simulation Assumptions

In reality, groundwater recharge behavior is very complex. To correctly simulate the behaviors or groundwater recharge, lots of accurate measurements and data are needed. In addition, the simulations require computers with high capacity to solve complex finite element models.

For simplification, assumptions are made such that we will not have to deal with all of these complicated issues. With appropriate assumptions, simulation models can be easier to solve and required fewer resources, but will give quite accurate results.

The basic assumptions that we use for this case study are as follows:

- 1) Soil characteristics are homogeneous and isotropic throughout the recharge area.
- 2) Unconfined aquifers beneath the areas have homogeneous characteristics, i.e. aquifers have the same depth, hydraulic conductivity, and storage coefficient everywhere.
- 3) There is no hysteresis for the soil properties, i.e. initial conditions will not affect retention and conductivity curves of the soil.
- 4) Recharge water is instantly applied to the area and is held constant during the recharge time.
- 5) Surface soils are dry, and groundwater tables are deep enough such that no groundwater is lost to evaporation.
- 6) Recharge water will not leave the recharge areas, and all of the recharge water can be withdrawn and used for irrigation.
- 7) Superposition is applied for a series of recharge facilities making the hydraulic gradient between two adjacent recharges equal to zero.

3.3 Groundwater recharge behavior

Groundwater recharge starts when supply water begins infiltrating into the ground and refills existing groundwater storage. The behaviors of the recharge can be classified into two stages:

- Unsaturated flow before recharge water reaches a groundwater table
- Saturated flow after recharge reaches a groundwater table

3.3.1 Behaviors of Unsaturated Flow

Unsaturated flow is defined by flow in which a porous medium still has some voids occupied by air. This stage starts right after recharge water first infiltrates into the ground and ends when a wetting front reaches the groundwater table. In this process, the soil can be filled fully with water if a water supply is continually fed over a long period of time.

The length of unsaturated flow is governed by infiltration rate, the rate at which water enters the soil at the surface. This depends mainly on soil properties, especially the hydraulic conductivity of the soil. Moreover, the duration also depends on the depth to groundwater.

Flow in the unsaturated zone is complicated due to complex relationship between water content, pressure head, and hydraulic conductivity. The forces that are involved in recharge behaviors are gravitational force, friction force and suction force (or negative pressure head) which bind water to soil particles through surface tension. The Richard's equation (1931), derived from mass balance equation and the Darcy's law, can be used to calculate infiltration rate and represent the behaviors of flow in unsaturated zone. We can solve the Richard equation numerically with the finite element method to determine infiltration rates and cumulative recharge fluxes. Eq.1 shows the simplified one-dimension form of the Richard's equation.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(D \frac{\partial \theta}{\partial z} + K \right) \dots\dots\dots(\text{Eq.1})$$

where θ = Soil Moisture Content
 t = Time
 z = Distance in z-direction
 K = Hydraulic Conductivity

The Green-Ampt equation is another well-known approach to estimate the infiltration rate and cumulative infiltration. The cumulative infiltration can be solved by the successive substitution method with Eq.2, and then substitute the cumulative infiltration for the infiltration rate in Eq.3.

$$F(t) = Kt + \varphi \Delta \theta \ln \left(1 + \frac{F(t)}{\varphi \Delta \theta} \right) \dots\dots\dots(\text{Eq.2})$$

$$f(t) = \frac{\partial F(t)}{\partial t} = K \left(\frac{\varphi \Delta \theta}{F(t)} + 1 \right) \dots\dots\dots(\text{Eq.3})$$

where $F(t)$ = Cumulative Infiltration at time t
 $f(t)$ = Infiltration rate at time t
 φ = Wetting front soil suction head
 $\Delta \theta$ = $\eta - \theta_i$
= Filled water content

However, the most important assumption that may be inappropriate to use in an artificial recharge problem is that the Green-Ampt equation is derived from a semi-infinite system, i.e. the groundwater table is located very deep and has no effect on recharge behavior.

Even though some assumptions of the Green-Ampt equation are not appropriate to deal with an artificial recharge problem, the result from this method is close to the one from numerical model using Richard's equation and finite elements. Flow in this stage is mainly in the vertical direction only. The infiltration rate is described in the vertical direction and depends on hydraulic conductivity, water content, porosity and soil suction. The result in Figure 3-2 shows that the infiltration rate is approaching the hydraulic conductivity of the soil.

Table 3-1: Green-Ampt Infiltration Parameters for Various Soil Classes.

Soil class	Porosity η	Effective porosity θ_e	Wetting front soil suction head ψ (cm)	Hydraulic conductivity K (cm/h)
Sand	0.437 (0.374–0.500)	0.417 (0.354–0.480)	4.95 (0.97–25.36)	11.78
Loamy sand	0.437 (0.363–0.506)	0.401 (0.329–0.473)	6.13 (1.35–27.94)	2.99
Sandy loam	0.453 (0.351–0.555)	0.412 (0.283–0.541)	11.01 (2.67–45.47)	1.09
Loam	0.463 (0.375–0.551)	0.434 (0.334–0.534)	8.89 (1.33–59.38)	0.34
Silt loam	0.501 (0.420–0.582)	0.486 (0.394–0.578)	16.68 (2.92–95.39)	0.65
Sandy clay loam	0.398 (0.332–0.464)	0.330 (0.235–0.425)	21.85 (4.42–108.0)	0.15
Clay loam	0.464 (0.409–0.519)	0.309 (0.279–0.501)	20.88 (4.79–91.10)	0.10
Silty clay loam	0.471 (0.418–0.524)	0.432 (0.347–0.517)	27.30 (5.67–131.50)	0.10
Sandy clay	0.430 (0.370–0.490)	0.321 (0.207–0.435)	23.90 (4.08–140.2)	0.06
Silty clay	0.479 (0.425–0.533)	0.423 (0.334–0.512)	29.22 (6.13–139.4)	0.05
Clay	0.475 (0.427–0.523)	0.385 (0.269–0.501)	31.63 (6.39–156.5)	0.03

The numbers in parentheses below each parameter are one standard deviation around the parameter value given. Source: Rawls, Brakensiek, and Miller, 1983.

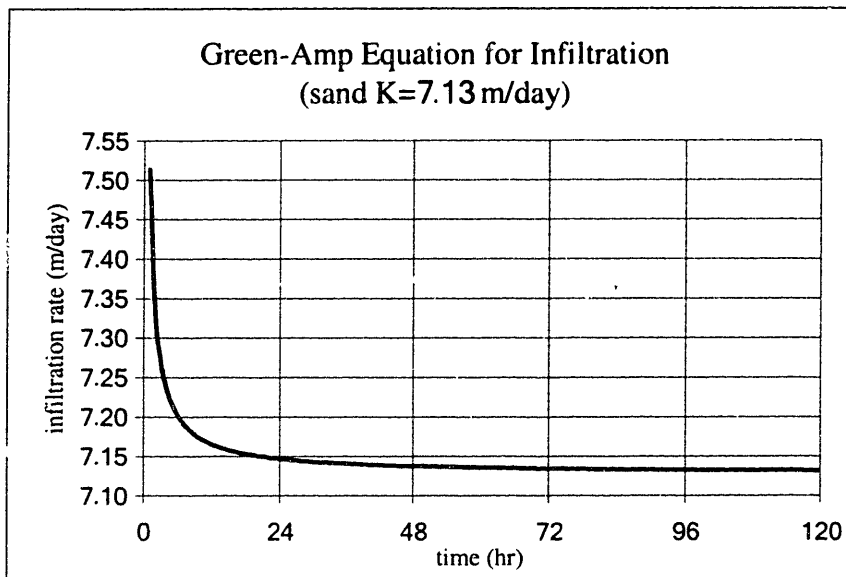


Figure 3-2: Infiltration Rate from Green-Amp Equation

Because coarse-grained soils are preferable for direct surface methods, the duration of unsaturated flow is relatively short when compared to the total recharge time. Depending on the groundwater depth, the recharge water may only take a few days to reach the water table, whereas the total recharge period lasts for several months. Therefore, the behaviors of this stage are not very important to the overall recharge process. By the time the wetting front reaches the groundwater table, the total amounts of recharge water will be approximately equal to the void spaces in porous media projected from the recharge area to the existing groundwater table.

Table 3-2: Representative Artificial Recharge Rates

Spreading Basins		Recharge Wells	
Location	Rate (m/day)	Location	Rate (m³/day)
California		California	
Los Angeles	0.7-1.9	Fresno	500-2200
Madera	0.3-1.2	Los Angeles	2900
San Gabriel River	0.6-1.6	Manhattan Beach	1000-2400
San Joaquin Valley	0.1-0.5	Orange Cove	1700-2200
Santa Ana River	0.5-2.9	San Fernando Valley	700
Santa Clara Valley	0.4-2.2	Tulare County	300
Tulare County	0.1		
Ventura County	0.4-0.5		
New Jersey		New Jersey	
East Orange	0.1	Newark	1500
Princeton	<0.1		
New York		Texas	
Long island	0.2-0.9	El Paso	5600
		High Plains	700-2700
Iowa		New York	
Des Moines	0.5	Long Island	500-5400
Washington		Florida	
Richland	2.3	Orlando	500-51,000
Massachusetts		Idaho	
Newton	1.3	Mud Lake	500-2400

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When the recharge is governed by unsaturated flow, the recharge rate will be approximately equal to the hydraulic conductivity. In fact, recharge rates are generally significantly less than the hydraulic conductivities of the soil. Hence, there should be some other mechanisms that retard the recharge rate and affect the overall recharge behavior.

3.3.2 Behavior of Saturated Flow

Saturated flow is defined by the flow of water in porous media in which water occupies all void spaces. This step begins after a wetting front reaches a groundwater table. Flow in the saturated zone deals with only two phases, solid and liquid phases, and Darcy's laws can be used to estimate the amounts of flow in the saturated zone. However, because water flows in both the vertical and horizontal directions, unlike the one directional unsaturated flow, the recharge behavior is not very easy to solve.

With the vertical flow, the concept of well injection such as the Theis equation cannot be used in this situation. Solving two-dimensional model numerically by the finite element method is the basic approach to estimate the recharge rate and total amount of recharge water. There are some analytical methods to solve for recharge rate, but they are complex, and can be used only in very specific cases.

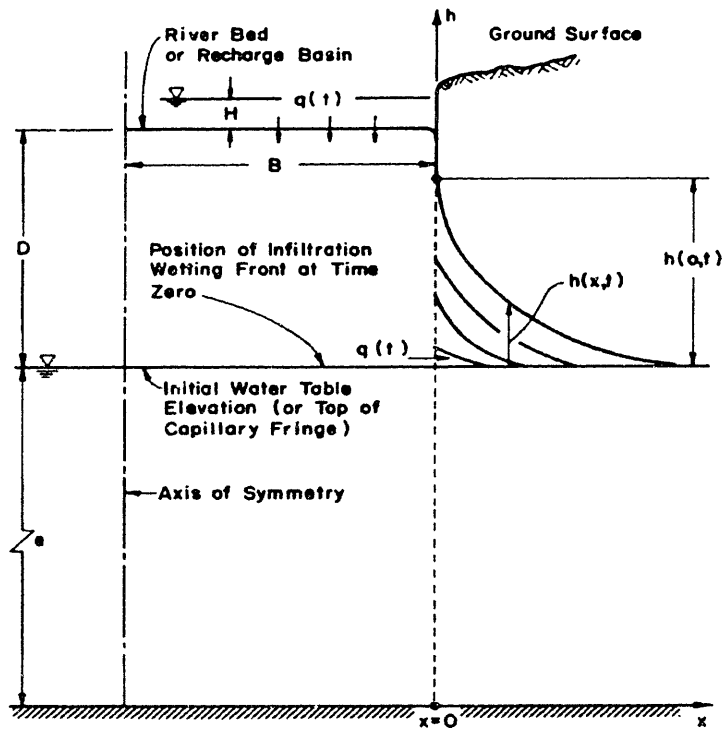


Figure 3-3: Groundwater Mound During Recharge (Asano, 1985)

The infiltration rate for artificial recharge ranges from 0.1 to 1.0 meter/day depending on location (Figure 3-2). Recall from the unsaturated flow in the previous section, the value of the infiltration rate is approximately equal to the hydraulic conductivity of the soil. This rate is significantly higher than what actually happens. Therefore, there should be some mechanisms that redistribute the hydraulic head and reduce the infiltration rate of the recharge water after the wetting front reaches the groundwater table.

Figure 3-3 and figure 3-4 show that, when the wetting front merges with the water in the saturated zone, the incoming recharge water, which once moved vertically, turns around and flows mainly below the water table. From this point on, there will be flow in the horizontal direction, and the water table elevation underneath the recharge area will rise up to the surface. A mound of water will consequently develop and drastically decrease the infiltration rate. Fortunately, the recharge rate does not become zero because the mound tends to dissipate by the hydraulic gradient in the horizontal direction that transports water away from the recharge area.

However, if a series of recharge area are presented, there is no hydraulic gradient between two adjacent furrows due to the superposition effect of these two recharge areas. Thus, the recharge rate will continue to decline until it reaches zero when all voids are filled up.

From the recharge simulation, three main factors that affect the recharge rate and the total amounts of recharge water are soil characteristics, depth to existing groundwater table, and spacing between two adjacent recharge areas.

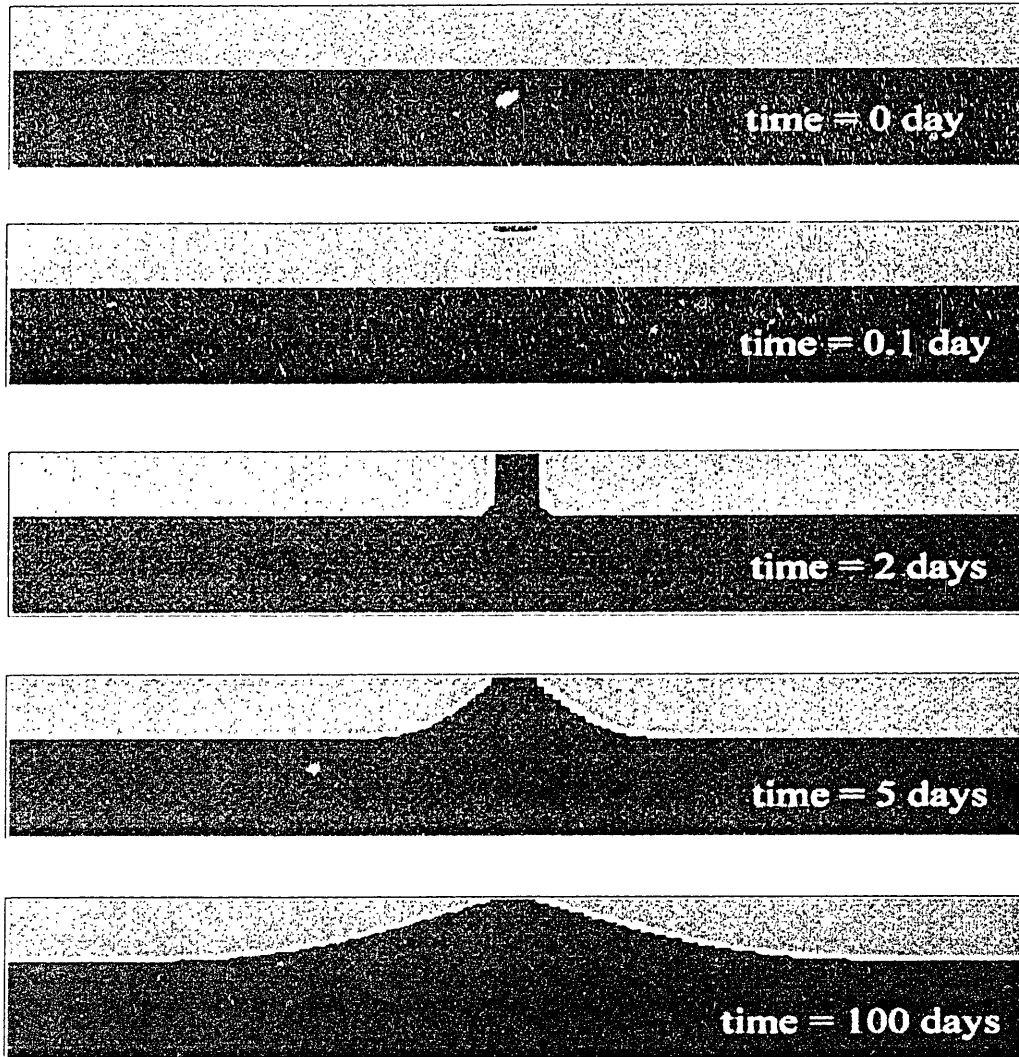


Figure 3-4: Artificial Recharge Simulation of Sandy Soil by Hydrus 2D

3.4 Effects of Soil Characteristics, Depth to Groundwater, and Spacing

In this recharge study, we are focusing on the purpose of irrigation. We would like to store as much water as we can during the low-demand period and then withdraw it in the high demand period. Thus, our objective for the artificial recharge is to select the artificial recharge site that can recharge the highest amounts of water in a limited time. In other words, select the artificial recharge area with the highest infiltration rate.

Regarding the recharge rate, there are three main factors that govern this behavior for a series of ditch and furrow systems: soil characteristics of recharge areas, depth to existing groundwater table beneath the recharge areas, and spacing between two adjacent recharge areas.

3.4.1 Effects of Soil Characteristics

Soil characteristics of the recharge areas play, perhaps, the most essential roles in groundwater recharge behaviors. Intuitively, we know that water can easily infiltrate through coarse-grained soil. In other words, with comparison to fine-grained soils, coarse-grained soils yield higher infiltration rates, and thus, allow more water to refill groundwater aquifers in the same amounts of time.

It is obvious to conclude that coarser grained soils are more suitable for groundwater recharge facility. However, the real problem is how to specify the differences quantitatively among various types of soils. We would like to know what the recharge rates for different soil types are, so that if the rates do not vary a lot, fine-grained soil may also be used as an alternative for artificial recharge.

To estimate the recharge rate, three soil types (sand, loamy sand and sandy loam) are selected. Their properties are taken from Carsel and Parrish, 1998 (See Table 3-3). Note that these parameters only represent very approximate averages for the different textural classes.

Table 3-3: Characteristic of Soil Types Used in the Recharge Simulation

Soil Type	Q_r	Q_s	K_s (m/day)	α (m^{-1})	n
Sand	0.045	0.43	7.128	14.5	2.68
Loamy Sand	0.057	0.41	3.502	12.4	2.28
Sandy Loam	0.065	0.41	1.061	7.5	1.89

Where

Q_r = Residual soil water content

Q_s = Saturated soil water content

K_s = Saturated Hydraulic Conductivity

α, n = Parameter in soil water retention function (van Genuchten:1980)

The simulation (Figure 3-5) shows that recharge fluxes of all soil types decrease with time, and vary significantly among each soil type. In the first couple of days before the wetting front reaches the groundwater table, depending on the soil type, recharge fluxes are much higher. Then they drop dramatically when the front reaches the groundwater table and continue to decline to some constant values.

As we anticipate, sand allows more recharge water to infiltrate than loamy sand, and sandy loam, respectively. Hydraulic conductivity seems to be the dominant factor that governs the overall behaviors of recharge water. The differences in recharge rates and cumulative recharges are quite significant among soil types. The result shows that the capacity to recharge water for sandy soil is about 1.5 and 2.5 times the capacities for loamy sand and sandy loam, respectively. These differences are as high as 2 to 4 million cubic meter differences if we recharge groundwater for 100 days with a single 1-kilometer long furrow. In other words, these differences in water are sufficient to grow grapes for 250 to 500 hectares in one season.

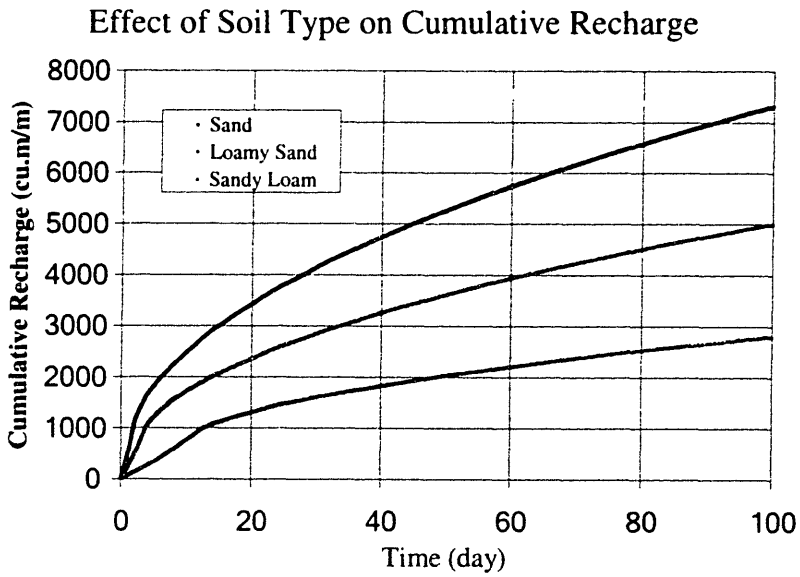
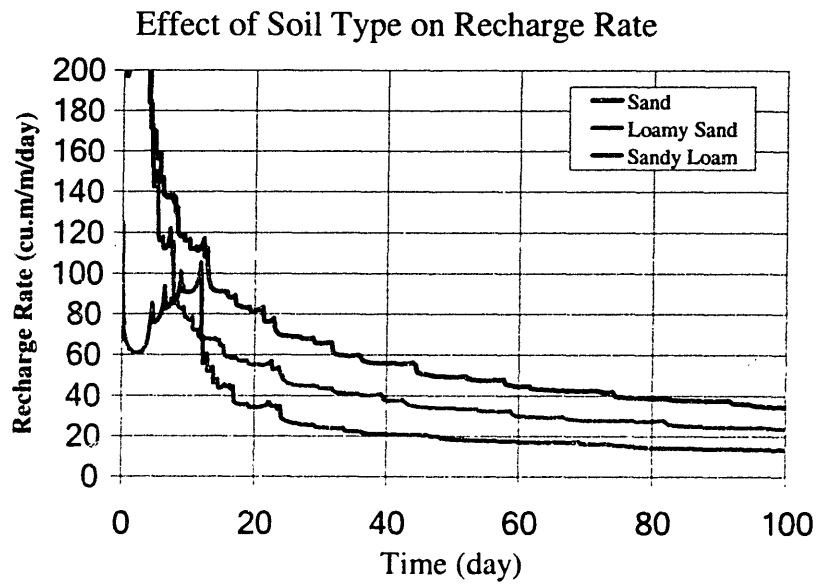


Figure 3-5: Effect of Soil Type to Recharge Rate and Cumulative Recharge Water

3.4.2 Effect of Depth to Groundwater Table

Beside the importance of soil characteristics on the recharge behaviors, the depth to the existing groundwater is another dominant factor that affects the recharge rate and total amounts of recharge water. From the behaviors of recharge in unsaturated and saturated stages, once recharge water hits an existing groundwater table, the recharge rate will

dramatically drop and continue to decline as a mound develops. Thus, larger recharge rates are expected from deeper groundwater areas.

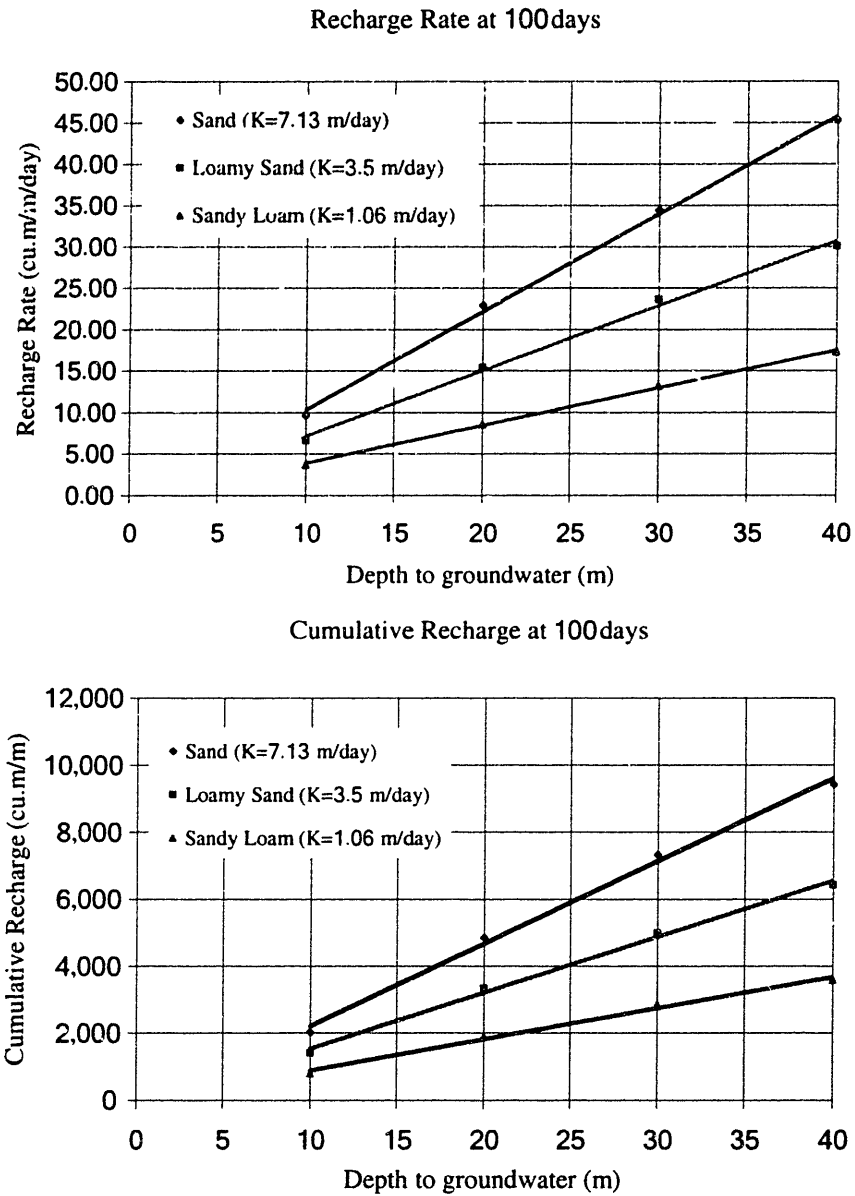


Figure 3-6: Effect of Depth to Groundwater on Recharge Rate and Cumulative Recharge

The simulation (Figure 3-6) shows that the groundwater depth has a great impact on the recharge rates and the total amounts of recharge water. The result shows that the recharge rates and cumulative recharges are linear functions with the depth to groundwater table. This factor is so important that it allows fine-grained soils to have a

higher recharge rate and larger amount of recharge water than coarser ones. For example, the total rechargeable water from sand with a water depth of 20 meters is almost 40% less than that from loamy sand with a water depth of 40 meters.

3.4.3 Effect of Spacing Between Adjacent Recharges

After the recharge water begins to merge with the existing groundwater in the aquifer, mound will develop and the recharge rate drops. Even though the mound tends to grow and expand with time, it will also dissipate due to the hydraulic head gradient in the horizontal direction moving water away from the recharge zone. Thus, the recharge rate will not decline sharply, nor become too small.

Unfortunately, in the case where a series of recharges are placed together side by side, the hydraulic gradients of these recharges will become zero due to superposition. As a consequence, the mound will continue to grow and the recharge rate drops more quickly. The closer these recharges are, the smaller amounts of water can refill groundwater aquifers. Therefore, we should select a suitable spacing between adjacent recharges. This spacing should be large enough to allow a considerable recharge rate but not take too much surface land.

The result shows that the effect of spacing is also a function of recharge time, soil type and depth to groundwater table. At the same recharge time, finer soils and deeper groundwater tables require less spacing. The relationship of recharge rate and cumulative amount of recharge water are non-linear functions of spacing between two adjacent recharge areas. These functions tend to approach some maximum value for particular recharge time. The suitable recharge spacing is selected from the point where the total amount of recharge water begins to be stable. This implies that an additional spacing will not allow any more water to refill the groundwater aquifer.

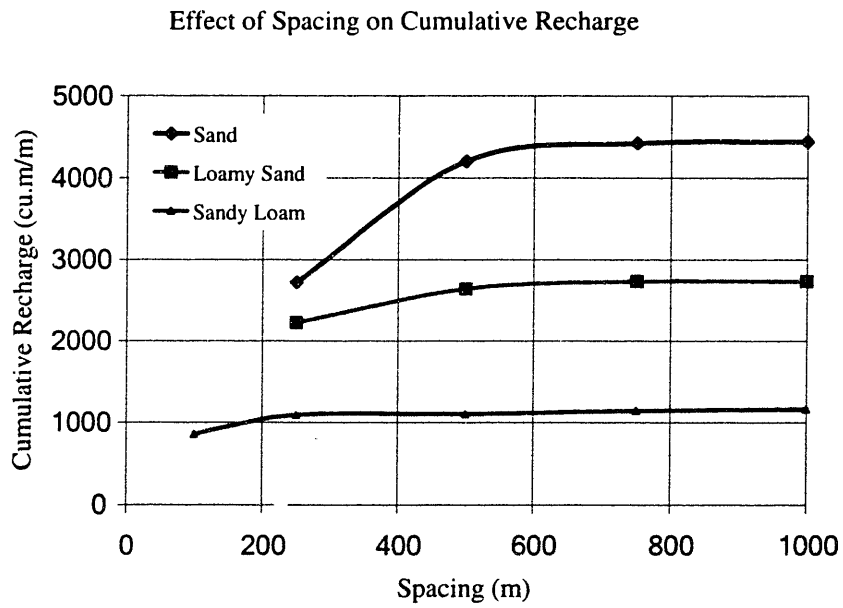
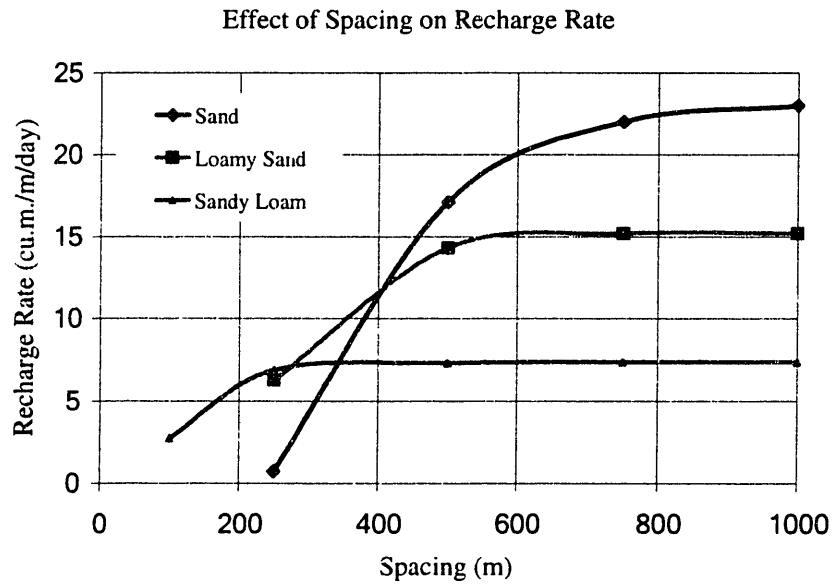


Figure 3-7 Effect of Spacing Between Two Adjacent Recharge Site

3.5 Water Recovery

In addition to the ability to recharge groundwater, the capacity to recover water from the subsurface storage is another important issue. Despite a large amount of water recharging the aquifer, the idea of artificial recharge is totally useless, if we cannot pump stored water back to use. Water recovery should be addressed for designing an effective artificial recharge facility, i.e. most or all of the recharge water should be able to recover.

There are many factors that govern the ability to recover recharged water, for example, transmissivity and specific yield of an aquifer, underground barriers, etc. Of many factors, transmissivity of an aquifer is the most important. This property indicates how fast the water can flow toward the pumping wells.

Even though for an aquifer with high transmissivity, the recharge water can leave the recharge area more quickly, we can pump the water at a higher rate. If the pumping period continues immediately after the recharge period, only insignificant amount of water can leave the recharge area. Moreover, as we pump the water, we are creating a cone of depression and a large hydraulic gradient that will force water to flow back toward the wells. Therefore, it is possible to recover all the recharged water within a limited time.

In contrast, if the aquifer has low transmissivity, we cannot pump water at a high rate, otherwise the wells will dry up because water cannot flow to the well fast enough. In this case, we may not be able to recover all the recharged water within a limited time. Thus, we do not obtain the most benefit from artificial recharge project.

3.6 Artificial Recharge Maintenance

To prevent clogging and enhance the ability to recharge water, occasional maintenance is needed for a direct surface recharge facility. Some methods used to prevent clogging

have already mentioned in section 2.3.3. The detail of water treatment and artificial recharge maintenance is beyond the scope of this study.

For a direct surface method, the most common way to prevent surface clogging is by scraping recharge surface or replacing the surface materials. Sometimes chemical substances are used to cure the clogging and enhance the infiltration rate. The frequency and cost of maintenance depends mainly on supply water properties and types of the artificial recharge facilities.

3.7 Conclusion for Groundwater Recharge Analysis

For irrigation purposes, we would like to construct artificial recharge facilities that can store as much water as possible in a limited time. Thus, we are concerned about the factors that will affect the recharge rates and total amounts of recharge water. For a better understanding, a computer simulation program is used to simulate several recharge behaviors based on different recharge factors.

The results show that the three main factors governing the recharge behaviors are the soil characteristics, the depth to groundwater table, and the spacing between two adjacent recharges. In order to have the highest recharge rate, these factors should follow the following conditions.

1. The selected areas should consist of coarse-grained soils, such as gravel or sand that has a high hydraulic conductivity. Coarse-grained soil allows us to supply more recharge water to refill aquifers in a limited amount of time. However, in reality, soil is mixed and heterogeneous. With soil size distribution, fine particles commonly fill the spacing between soil elements. This notably reduces the capacity to recharge water. Hence, in reality, reduction factor of 5 can be

expected when applying the recharge rate from the simulation with a homogeneous soil profile.

2. The selected areas should have deep groundwater tables. Deep groundwater table allow more water to infiltrate into aquifers. However, the costs to pump water back for agricultural purpose should be considered when selecting a suitable groundwater depth.

With the assumption that pumping begins immediately after the recharge time, the mound is not yet dissipated at the beginning of the pumping period. Thus, the energy cost to withdraw water does not depends much on the original groundwater table at first. Never the less, the water table will continue to drop which makes the existing groundwater depth becomes significant factor in determining the required energy to pump the groundwater back to use.

3. When we apply a series of recharge systems, we should provide adequate spacing between two adjacent recharge sites, depending on total recharge time, soil type, and also groundwater depth. The spacing should be great enough to allow significant amount of water to recharge the aquifer. For particular conditions, there is a suitable spacing such that further distance does not yield more recharge water. Besides, additional spacing leads to higher construction, operation and maintenance costs.

We can use these criteria to select candidate sites for artificial recharge in the San Joaquin Valley. After the proposed site is selected, more simulation should be conduct according to the condition of the site to determine the recharge rate and the total amounts of recharge water. Then, we use these results to evaluate the economic feasibility of the project. If the potential benefits exceed the costs, this project is feasible and should be carried out to contribute benefits to the area.

Chapter 4

Site Selection and Economic Analysis

From the simulation results, we can now select candidate sites for the artificial recharge project that satisfy with fundamental criteria in the previous section. After a suitable site is selected, economic analysis should be performed to evaluate the feasibility of applying the artificial recharge project to the area.

4.1 Artificial Recharge Site Selection

In this study, the artificial recharge site is chosen by using ArcView GIS to select the areas in the San Joaquin Valley that have capacities to recharge the largest amounts of water in a limited time and are intuitively practical to construct.

4.1.1 ArcView GIS

Geographical Information Systems, GIS, is a computer system that is capable of assembling, storing, manipulating, and displaying geographically referenced information. GIS technology can be used for scientific investigations, resource management, and development planning. Practitioners also regard the total GIS as including operating personnel and the data that go into the system.

Among many GIS software currently available, ArcView GIS is the most well known program widely used in many organizations. This program is developed by Environmental Research Systems, Inc. By using ArcView GIS to manage recharge data (surface elevation, groundwater level, soil type, land use, etc.), we can easily observe the

relationships between these data and then select the suitable areas for our artificial recharge purpose.

4.1.2 Data for Artificial Recharge Site Selection

Large numbers of information has been used to select appropriated artificial recharge sites in the San Joaquin Valley with ArcView GIS. This data is as follows:

1. Digital Surface Elevation (DEMs)

Surface elevation data is obtained from U.S.G.S. Geographic Data Download website (<http://edc.usgs.gov/doc/edchome/ndcddb/ndcddb.html>). This data is used as a guideline to see the general topographic of the area and locate flat plains, foothill slopes, and mountains within the San Joaquin area.

2. Groundwater Elevation

The groundwater elevations are provided by California Department of Water Resources, Division of Planning and Local Assistance (<http://well.water.ca.gov>). The groundwater elevation data is used in ArcView GIS to construct the contours of the groundwater elevation and the depth to groundwater table. The depth to groundwater table is one important factor to determine the recharge rates and total amounts of recharge water in a limited time.

3. Soil Characteristics

Soil data is provided by State Soil Geographic (STATSGO), United States Department of Agriculture. This data is, perhaps, the most important but the most inaccurate information for estimating the recharge rates and total amounts of recharge water. The soil data is at 1:250,000 scales, which is quite a coarse resolution. Because actual soil profiles are very complex and heterogeneous, if we expect to have accurate results, onsite investigation is strongly recommended.

4. Surface Land Use

Land use data is obtained from Department of Water Resources, Division of Planning and Local Assistance (<http://www.waterplan.water.ca.gov/>). This data provides an additional basis for selecting a more reasonable artificial recharge site (i.e. avoid construction in the urban area.)

By projecting all data together in ArcView GIS, we can see the relationships of each property of the study area. With the relation projected in the same view we can simply get rid of any area that is unqualified to be an effective artificial recharge site, and propose the areas that are suitable to be used for artificial recharge purpose.

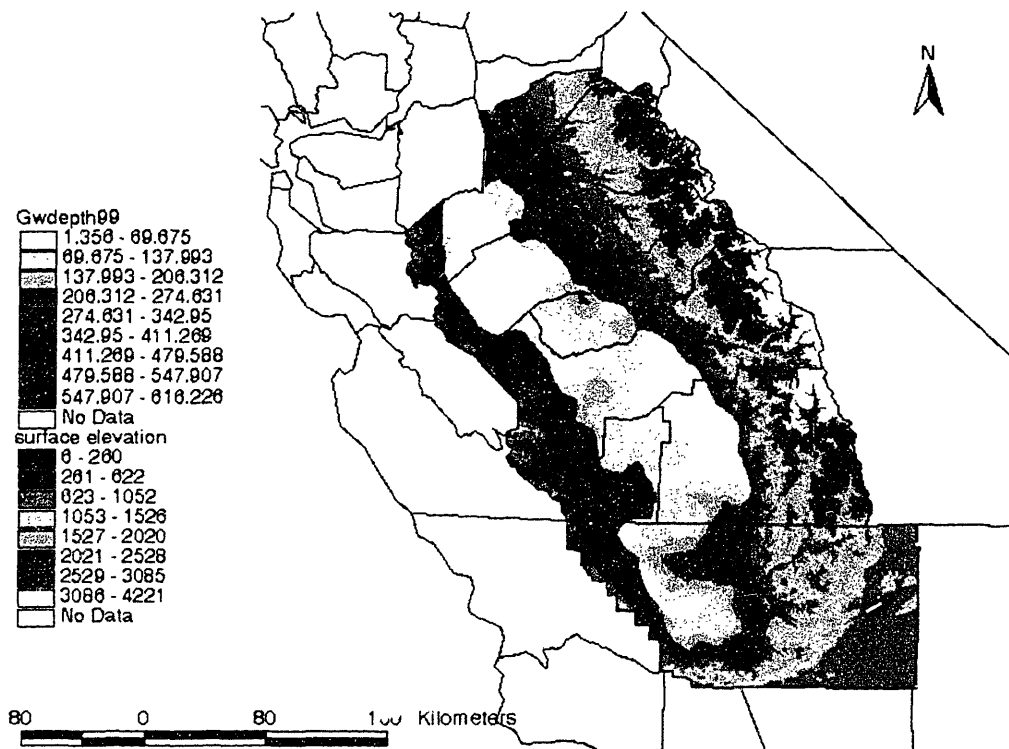


Figure 4-1: Example of Groundwater Depth and Surface Elevation Data Using ArcView GIS

4.1.3 Proposed Artificial Recharge Site in the San Joaquin Valley Area

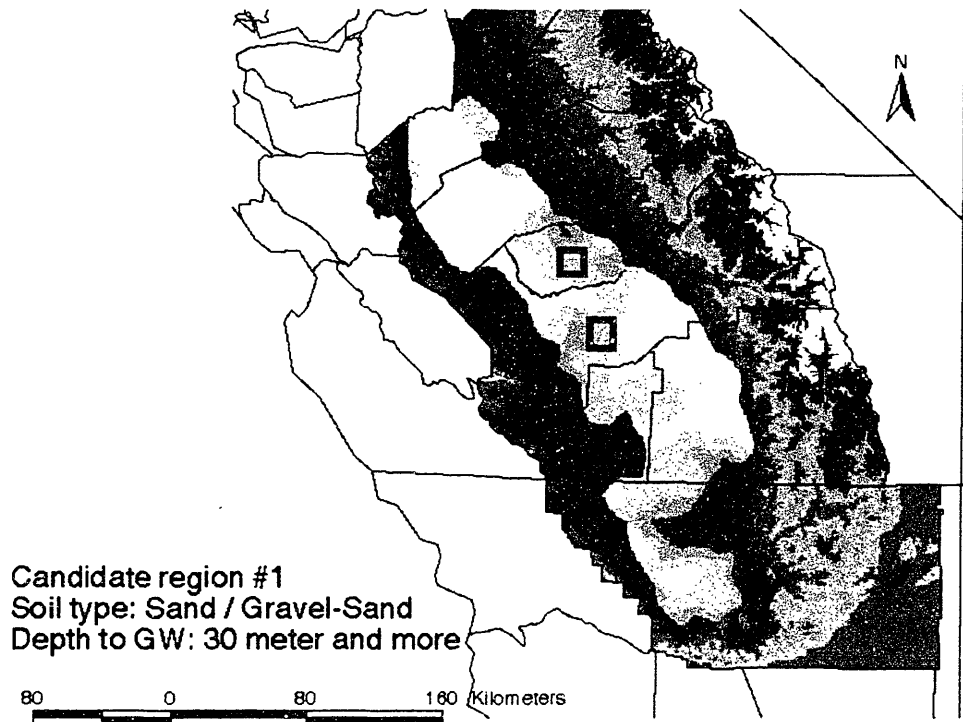


Figure 4-2: Proposed Artificial Recharge Site by ArcView GIS

The following criteria are used to select the appropriate artificial recharge site in the San Joaquin Valley, California for irrigation purpose.

1. The proposed sites should consist of coarse-grained soils to allow large amount of water to recharge into the ground. Thus, lands with gravel and sand are our primary interest.
2. The proposed sites should have relatively deep groundwater levels, but the levels should not be too low to pump water back to use in irrigations. In general, areas with the groundwater depth less than approximately 30 meters are acceptable.
3. The proposed sites should not be located in an urban area because the surface land is expensive and there are many restrictions for the surface land use.
4. The proposed site should be located near surface water supplies that can provide water during the recharge time.

From these criteria, two areas in Madera and Kings basins are proposed to construct the groundwater recharge facilities. Details of these proposed sites are shown in Table 4-1. Because the irrigation season normally begins in May and ends in September, and the surface water supplies originate from the snow in Nevada Mountain, the recharge facilities are planned to operate from February to May, or approximately 120 days per year.

The result shows that significant amounts of water can be recharged in both areas. For the Madera basin, the total amount of recharge water is very close to the annual overdraft. This recharge project, if it is economically feasible, can significantly help solve the overdraft problem in this region.

Table 4-1: Details of Proposed Artificial Recharge Site for the San Joaquin Valley, California

	Madera Basins	Kings Basins (Fresno)
Site Selection		
Land Availability	4 x 6 km ²	14 x 8 km ²
Diverted River	San Joaquin River (at Millerton)	Kings River (at Pine Flat)
Recharge Duration	120 Days (Dec. – Apr.)	120 Days (Dec. – Apr.)
Surface Water Available (During Recharge Time)	823 million m ³	633 million m ³
Recharge Strategies		
Recharge Length	1 km.	1 km.
Spacing Between Recharge Areas	500 m.	500 m.
Number of Recharge Areas	2	2
Approximate Recharge Rate	8000 m ³ /m/season	8000 m ³ /m/season
Total Recharge Water (during recharge time)	32 million m ³	32 million m ³
Percentage of Surface Water Recharged	4 %	5%
Benefits Gained		
Pumping Periods	150 days (Apr. – Sep.)	150 days (Apr. – Sep.)
Available Pumping Rate	0.2 million m ³ /day	0.2 million m ³ /day
Additional Irrigation Land Benefit	8000 Acres* ¹	8000 Acres* ¹
Annual Overdraft of the Basin	30,000 acre-feet	336,000 acre-feet
Percentage of Annual Overdraft Recharged	87 %	8 %

Note: *¹ Assume water needed for irrigation is 1 meter per season

4.2 Economic Analysis and Feasibility of the Project

Economic profitability is an important aspect of a project feasibility analysis. For any project to be implemented, it must be economically feasible. In other words, the benefits expected to receive from the project must surpass the total expense of the project.

4.2.1 Economic Analysis Scheme

For the artificial recharge scheme, the project will be economically feasible if the benefits from provide additional recharge water exceed the total costs of recharge facilities. In reality, the costs and benefits are very difficult to define. For example, some costs and benefits are dealing with feelings of people that are very subjective and difficult to translate into an exact amount of money.

In this study, we will not cover all the feasibility analysis that must be done in the real project. Our objective is only to give an approximation of the total costs and benefits from the artificial recharge project. Therefore, we will only discuss the possibility of implementing an artificial project without making exact conclusions on the feasibility of the artificial recharge project.

4.2.2 Estimation of the Costs from Artificial Recharge

We assume that a group of farmers constructs the groundwater recharge facilities and share the water within the group. Therefore, the main costs of artificial recharge are the land acquisition cost, construction cost, operation and maintenance cost, and supplied water cost.

- Cost of Land acquisition

From the assumption that a group of farmers forms the artificial recharge facilities, we assume that they have their own land to grow crops. The only additional land needed is the land for the artificial recharge facilities, including the spacing between

recharge series. This land cost in California depends on location and land type. Table A-1 shows that the cost to buy irrigated field crop in the Great Valley is approximately \$3000 per acre.

- **Cost of Construction**

Cost of construction is mainly the ditch excavation work and removal of the soil. This cost varies significantly with soil types, labor cost, slope of the area, and size of earthwork. The average cost to construct a ditch with approximately 20-meter width by 2-meter depth is about \$500 per meter in California.

- **Cost of Maintenance**

Occasionally, the recharge facilities must be maintained to prevent clogging. Scratching the recharge surface is a common method to increase the infiltration rate for the surface recharge techniques. We assume that the annual maintenance cost is 5% of the construction cost.

- **Cost of Pumping Groundwater**

If we assume that all the recharge water can be restored, the total amount of pumped water is 32 million m³. From Table A-2 with pumping efficiently of 50%, the cost required to lift groundwater 30 meter high is about \$0.67 per acre-feet or \$550 per million m³.

- **Cost of Recharge Water**

The recharge water is taken from the natural stream nearby. Regarding Department of Water Resources, Californians pay \$0.01 to \$0.28 per cubic meter of water for irrigation purpose. Because we purchase surface water in the low demand period, we assume the cost of recharge water to be \$0.05/m³. Note that farmers will have to pay for this the same amounts of water to grow of crop in the San Joaquin area, regardless of the artificial recharge facilities.

Suppose that the project time is 15 years, the discount rate is 5%, and the conditions for Madera and Kings basin are the same. Annual expense distributed within 15 years can be approximated as in Table 4-2. Note that cost of recharge water is approximately 70% of total annual cost.

Table 4-2: Approximate Annual Cost of Artificial Recharge Project

List	Unit Cost	Total Unit	Cost
Land Acquisition	\$3000/acre	125 acres	\$375,000.
Construction	\$500/meter	2x1000 meters	\$1,000,000.
<i>Total Fix Cost</i>			\$1,375,000.
Represented Amortization Cost			\$132,500.
Maintenance	5% Construction cost/year		\$50,000. /year
Recharge Water	\$0.05/m ³	32x10 ⁶ m ³ /year	\$1,600,000. /year
Pumping operation	\$0.0164/m ³	32x10 ⁶ m ³ /year	\$512,000. /year
O/M Cost			\$2,162,000. /year
Total Annual Cost			\$2,294,500. /year

4.2.3 Estimation of the Benefits from Artificial Recharge

For simplification, we will only consider additional revenues gained from supplementary recharge water as a representative for benefits earned from the project. We need to keep in mind that the revenues presented here are not equal to direct benefits from artificial recharge project because other costs of irrigation (other than water supply) are not included in the estimation.

Annual revenues are calculated by:

- Obtain water need for each crop type (c2) from Table A-3.
- Calculate additional land for irrigation (c3) by dividing total amount of recharge water (32 million cubic meter) with water need (c2). We assume that all recharge water can be pumped for irrigation.
- Obtain crop yield (c4) from Table A-4 and crop price (c5) from United States Department of Agriculture [16].
- Calculate estimated revenue by multiplying additional land (c3), crop yield (c4), and crop price (c5).

The revenues from different crop types commonly grown in California are presented in Table 4-3.

Table 4-3: Potential Crop Revenues from Artificial Recharge Project

Crop Type	Water Need (mm/season) (c2)	Additional Land (Acre) (c3)	Crop Yields (Tons/Acre) (c4)	Crop Prices (\$/ton) (c5)	Revenue (10⁶ \$) (c6)
Grapes	800	10000	7.5	428	32.1
Lettuce	600	13200	17.0	380	85.2
Almond	500	15800	0.9	2900	41.0
Cotton	1000	7900	0.6	1460	6.9
Tomatoes	700	11300	30.9	700	244.4

4.2.4 Feasibility of the Project

From the results in Table 4-2 and Table 4-3, the total annual costs are approximately 2.3 million dollars, while the revenues from crop production as a result of artificial project range from 30 million dollars to as high as 240 million dollars (excluding cotton). In other words, artificial recharge costs are only about 1% to 6% of total revenues. Thus, we can conclude that the costs to construct, operate and maintain artificial recharge facilities are relatively small compared to annual crop revenue, which shows that the artificial recharge concept can be feasible to apply.

For more accuracy, a detailed analysis should be done to confirm the feasibility of the project, i.e. to insure that the actual benefits from artificial recharge project exceeds the total costs. Since the total costs and benefits depend greatly on locations and conditions of the area; hence, the feasibility study for each project should be done separately and we need to make sure that the analysis considers and risk analysis as well as the average expenses and average benefits gained.

Chapter 5

Conclusions

In this final chapter, we present a summary of our study about artificial recharge for conjunctive use in irrigation and recommend areas for further work.

5.1 Summary of Project

Our objectives are 1) to understand the behavior of artificial groundwater recharge and the use of groundwater aquifers for alternative water storage, 2) to select a suitable area, and 3) to evaluate the economic feasibility of an artificial recharge project. To study the behavior of recharge water, a computer model is used to simulate the behavior of recharge water in different conditions. In addition, a GIS program is used to identify suitable land conditions for applying artificial recharge facilities. Costs and revenues are estimated to evaluate the potential to apply artificial recharge for an actual situation.

5.1.1 Artificial Recharge Methods for Conjunctive Use in Irrigation

For conjunctive use in irrigation, we would like to store water in a groundwater aquifer during the low-demand season and then withdraw it to use in high-demand season. Commonly in irrigation areas, land value is not very high compared to an urban area, and there are fewer restrictions in the surface land use. Therefore, direct surface recharge methods are recommended for irrigation purposes due to cheaper cost of construction, operation and maintenance.

5.1.2 Important Factors in Artificial Recharge

Regarding the direct surface method, a ditch and furrow system is simulated in the Hydrus 2-D program to observe recharge behavior in different conditions. From the result, there are three main factors that affect the recharge rate and the total amounts of recharge water. These three factors are the soil properties, the depth to groundwater table, and the spacing between two adjacent recharge areas.

Recharge areas consisting of coarse-grained soil (i.e. gravel or sand) and deep groundwater table tend to have significantly higher recharge rates. To recharge the highest amounts of water, an artificial recharge area should lie over coarse-grained soil and have relatively deep groundwater table. However, with variation of soil properties, compaction, and wide-distribution of grain size, the actual recharge rate is expected to be notably lower than the result from the simulation with homogeneous soil properties.

Spacing between two adjacent recharge areas can also limit the allowable recharge rates of artificial recharge facilities. In practice, depending on soil types, depth to the groundwater table and the total recharge times, there is a specific spacing where additional spacing will not allow any further increase in the recharge rate. This spacing should be used to construct a series of recharge facilities.

5.1.3 Ability to Pump Stored Water for Irrigation

Abilities to pump stored water depend on many factors, but the most important one is the transmissivity of the aquifer. The total amount of water that we can pump in a limited time depends on allowable pumping rate, which also depends strongly on the transmissivity of the aquifer, i.e. how fast water can flow to the pumping wells.

If the transmissivity of the aquifer is high, even though water can quickly leave the recharge area, it is possible to pump the same amount of water in which we recharge without dissipating groundwater table. The recharge water leaving the recharge area will

tend to flow back and refill the pumped water due to hydraulic gradient toward pumping wells.

In contrast, if the aquifer has low transmissivity, we cannot pump at the rate, which will withdraw all of the recharge water back to use in a limited time. In this case, we cannot obtain the most benefit from artificial recharge project by pumping all the recharge water. Therefore, transmissivity of an aquifer is another important factor that should be included in designing the recharge facilities.

5.1.4 Feasibility of the Artificial Recharge Project

The total costs of construction, operation and maintenance of the artificial recharges facilities are considerably lower than the revenues gained as a benefit from the artificial recharge program. Even though the total revenues cannot directly present the benefits from artificial recharge facilities, they give us some benchmarks to compare with the total costs of the artificial recharge project. Due to the relatively low expenses of the project, the artificial recharge project seems practical to apply for the purpose of conjunctive use in irrigation. However, a more detailed study of economic feasibility is recommended for more accurate results.

5.2 Recommendations for Future Research

5.2.1 Radial Configuration Artificial Recharge

Many techniques are presented in the direct subsurface recharge method. In addition to the ditch and furrow technique that we simulated in this study surface infiltration, basins provide another technique that is commonly used in artificial recharge. The shape of a recharge basin is typically a square which we can simulate the behaviors of recharge water with approximate radial configuration.

5.2.2 Actual Recharge Behaviors vs. Simulation Behaviors

In the simulation, we have set up many assumptions that are sometimes inappropriate to be used in an actual situation. These assumptions may result to inaccurate results. Moreover, many input parameters used in the simulation may not be detailed enough to give us the correct outputs. Thus, field investigation and in situ experiment is suggested to compare with the simulated results. The comparison should give us some idea about the accuracy of the simulation, the quality of the input data, and the suitability of the assumptions that we used.

5.2.3 Detailed Simulation and Economic Analysis

To practically construct any artificial recharge facilities, more accurate recharge behaviors, and detailed economic analysis are needed. We need to ensure that the behavior of actual recharge facilities will follow the results from the simulation and that the recharge project will be beneficial feasible. Therefore, detailed data for each individual recharge site should be collected and used for the simulations and economic analysis. We have to keep in mind that these detailed data vary a lot over space and time, and they have a great effect on recharge behavior and the feasibility of the project.

Appendix A

Artificial Recharge Simulation Models

A.1 Symmetrical Model Results

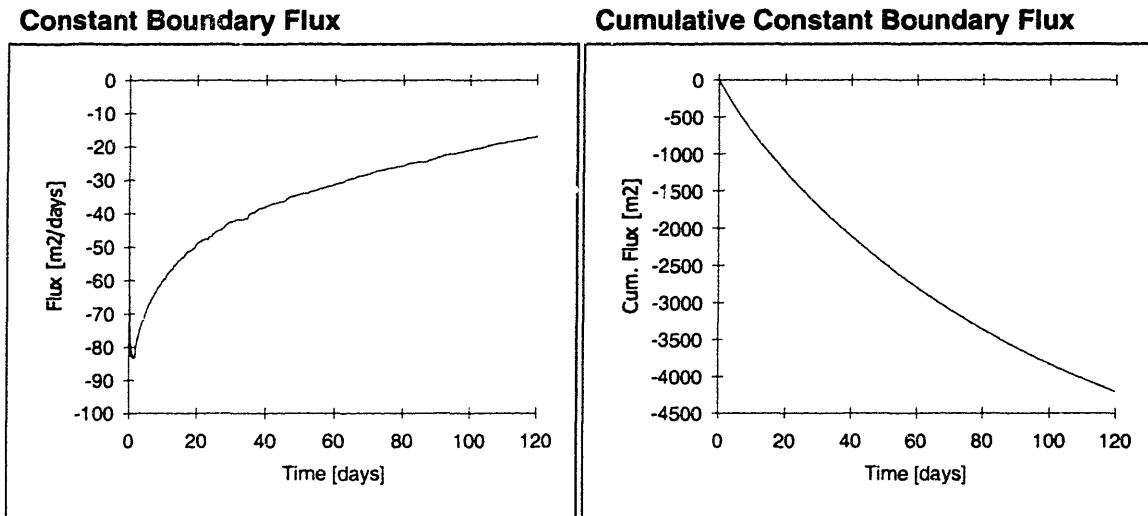


Figure A-1: Recharge Rate and Cumulative Recharge Rate of Proposed Artificial Recharge Sites (Sandy Soil, Groundwater 30 m. depth, Spacing 500 m.)

A.2 Economic Analysis: Costs

Table A-1: Land Acquisition Cost in the Great Valley, California

Surface Land Use	cost/acre
Rice	\$4,000
Vegetable crops	\$4,500
Irrigated field crops	\$3,000
Rangeland	\$700
Walnuts	\$8,500
Pears	\$8,000
Vineyards	\$20,000

Table A-2: Energy Cost to Required to Lift One Acre-foot of Water One Foot of Elevation

Overall Plant Efficiency (%)	Energy to Lift One Acre-foot (325,851 gallons) One Foot in Elevation (kWh)	Cost to Lift One Acre-Foot One Foot in Elevation (\$0.10/kWh)
100	1.02	\$.102
75	1.37	.137
70	1.46	.146
65	1.58	.158
60	1.71	.171
55	1.86	.186
50	2.05	.205
45	2.28	.228
40	2.56	.256

(Sources: University of California Cooperative Extension - Tulare County
Revised: January 28, 1998)

A.3 Economic Analysis: Benefits

Table A-3: Crop Water Needs and Sensitivity to Drought

Crop	Crop Water Need (mm/total growing period)	Sensitivity to Drought
Alfalfa	800-1600	low-medium
Banana	1200-2200	high
Barley/Oats/Wheat	450-650	low-medium
Bean	300-500	medium-high
Cabbage	350-500	medium-high
Citrus	900-1200	low-medium
Cotton	700-1300	low
Maize	500-800	medium-high
Melon	400-600	medium-high
Onion	350-550	medium-high
Peanut	500-700	low-medium
Pea	350-500	medium-high
Pepper	600-900	medium-high
Potato	500-700	high
Rice (paddy)	450-700	high
Sorghum/Millet	450-650	low
Soybean	450-700	low-medium
Sugarbeet	550-750	low-medium
Sugarcane	1500-2500	high
Sunflower	600-1000	low-medium
Tomato	400-800	medium-high

(Sources: Brouwer C., Irrigation Water Management)

Table A-4: Average Crop Yields for Difference Crop Types (Ton/Acre)

<i>Crop</i>	<i>1960-62</i>	<i>1969-71</i>	<i>1980-82</i>	<i>1989-91</i>	<i>Percent Increase 1960/62-1989/91</i>
Cotton	0.53	0.41	0.54	0.61	15.1
Rice	2.36	2.70	3.42	3.88	64.4
Corn, grain	2.71	2.65	3.69	4.48	65.3
Wheat	0.80	1.20	2.44	2.45 ¹⁰	206.0
Alfalfa	5.10	5.60	6.47	6.65 ¹⁰	30.4
Processed tomatoes	17.12	22.9	25.10	30.90	80.7
Lettuce	9.20	11.00	14.70	17.00	84.8
Oranges	7.10	9.40	11.60	13.80 ¹⁰	94.4
Avocados	1.92	2.83	3.01	— ¹⁰	56.8
Prunes (dried)	1.73	1.39	2.16	2.39	38.2
Almonds (shelled)	0.37	0.51	0.55	0.90	76.4
Wine grapes	5.46 ¹¹	5.22	7.09	7.53	37.9
SIMPLE AVERAGE					70.9

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