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William K Johnson, Laura Mumford, Marcus Romani

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Artificial recharge plays a significant role in conjunctive use where surface water is replenished by groundwater. Examples are presented of sites selected from across the United States, where conjunctive use systems exist and where artificial recharge either exists or is planned.

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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FOREWORD

Conjunctive use of surface and groundwater resources is both a present reality and future prospect. This document reports both. Examples are presented of sites, selected from across the United States, where conjunctive use systems exist and where artificial recharge either exists or is planned. Artificial recharge plays a significant role in conjunctive use where surface water is used to replenish groundwater. Much can be learned from examining these systems. They serve as a beginning point, as a base, as an example of what conjunctive use is, the needs it meets and how it functions. Future prospects for conjunctive use systems are bright and planning for future systems is best rooted in what has gone on before . . . the present reality.

Preparation of this document was itself a conjunctive effort. A variety of talents were utilized. Laura Mumford worked on the study from start to finish, contributing the section on selected conjunctive use systems and editing text and drawings throughout. Marcus Romani contributed the section on artificial recharge and some of the planning information. Lynne Stevenson provided valuable library research assistance and Ann Chance typed both drafts and final copy of the text. Bill Johnson was project engineer for the study under the supervision of Darryl W. Davis, Chief, Planning Analysis Branch and Bill S. Eichert, Director, The Hydrologic Engineering Center. Funding for the study was provided by the Institute for Water Resources Corps of Engineers. James Dalton was coordinator under the direction of Kyle Schilling, Chief Policy Division and J. Randall Hanchey, Director.

SURVEY OF CONJUNCTIVE USE AND

ARTIFICIAL RECHARGE ACTIVITY IN THE UNITED STATES

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INTRODUCTION

Purpose and Scope

Information on conjunctive use and artificial recharge systems in the United States may be characterized as being sparsely and randomly distributed across the landscape of technical literature. It is the purpose of this document to pull together this information, or as much of it as is possible, into a single document and to describe selected systems to illustrate their nature and purpose. To do this the document has been divided into four major sections: Selected Conjunctive Use Systems, Selected Artificial Recharge Sites, Planning Conjunctive Use Systems, and Bibliography.

Selected Conjunctive Use Systems. Surface and groundwater supplies, when drawn together to meet water supply needs, constitute conjunctive use systems. This section examines eight such systems and briefly describes those features which define their conjunctive nature. They provide the reader with examples from which additional information can be obtained for a detailed study.

Selected Artificial Recharge Sites. Current artificial recharge activity is presented in two ways. First, the results of a national survey of artificial recharge activity are presented with map and accompanying table for ninety sites. Reference documents are cited to enable the reader to obtain further information. Second, seven artificial recharge sites are presented with a brief description and sketch. These examples provide the reader with somewhat more detailed information at selected sites.

Planning Conjunctive Use Systems. To illustrate some of the basic concepts related to planning conjunctive use and methods of artificial recharge, a section is presented which describes the important features. Also, several reference documents are cited.

Bibliography. The concluding section of this document presents a bibliography of both conjunctive use and artificial recharge literature. This should be useful to the reader in conducting an inquiry beyond the scope of this study.

Historical Context

In the history of United States' water resource development, particularly in the West and California, the concept of integrating the use of surface water and groundwater evolved as water planners developed plans to meet future regional water needs. In 1921, the California State Legislature made the first of a series of appropriations for investigations of plans for the "conservation, control, storage, distribution, and application of all the water of the State." Ten years later, the Division of Water Resources submitted to the legislature the State Water Plan. The concept of conjunctive use was central to this plan.

> "The plan for the development of the Great Central Valley comprises surface storage reservoirs and conveyance systems, operated in conjunction with underground reservoirs." (State of California, 1930)

In 1949, the United States Bureau of Reclamation's "Central Valley Basin" plan continued the concept,

> "The primary purpose of the major reservoirs . . . . would be the regulation of the rivers by storage of water during periods of surplus run-off for subsequent release during periods of deficient supply . . A part of the supply from the reservoirs would be used to replenish the underground basins from which water is pumped by means of wells as needed. These underground basins are estimated to have a usable capacity of about 20,000,000 acre-feet, and their use is essential to the economical development of the water resources of the basin." (U.S. Bureau of Reclamation, 1949)

During the 1950's, the concept of conjunctive use continued to develop in the professional literature and receive a recognition of its own (Simpson, 1951; Banks, 1952; Todd, 1959). The National Water Commission in 1973 called for conjunctive use management on a national scale,

> "The Commission recommends that States in which groundwater is an important source of supply commence conjunctive management of surface water (including imported water) and groundwater through public management agencies." (National Water Commission, 1973).

Implicit in the National Water Commission recommendation is the fact that most of the groundwater reservoirs in the nation are being depleted by pumping. Integration of surface and groundwater reservoirs allows the two supply sources to be operated conjunctively - the same concept which emerged in California's first State Water Plan in 1930. It is the resource which is managed and this involves,

> " . . . the planned use of underground storage in coordination with surface water supplies to increase the yield of the total water resource."

More recently, the concept has been broadened in a way that both conjunctive management of the supply and conjunctive management of the use are included. Templer (1980) defines conjunctive management as,

> " . . . the situation where water in two or more phases of the hydrologic cycle are managed together as an integrated resource."

Two interpretations are possible. The first, the historic concept, where surplus surface water replenishes groundwater and the two are managed conjunctively, and second, the situation where surface and groundwater are supply sources and are integrated at the distribution or use level. In this situation, the supplies are used conjunctively in that both supply the same distribution system, however, they do not supply each other. Yevjevich (1979) describes a variety of combinations of distribution networks which are supplied from surface and groundwater resources but are not integrated themselves.

Examples of both types of conjunctive use may be found across the country. In the West, Southwest, and Midwest, the integration of surface and groundwater supplies is commonplace. In the East, many examples of distributing and mixing water from surface and groundwater sources can be found. In one of the following sections, eight examples of both type systems are described.

Role of the Corps of Engineers

The Corps of Engineers, as an agency which develops, maintains and regulates surface waters, can play an important role in conjunctive use planning and development. Traditionally, the Corps has developed supply sources by providing water supply storage in new reservoirs. In most cases, this storage is included with storage for other purposes such as flood control and hydroelectric power. Such a new supply source can be integrated into a conjunctive management plan.

Another means of providing water supply storage is through reallocation of storage at existing reservoirs. In Corps reservoirs, which do not have water supply, the opportunity exists to reallocate existing storage. Such reallocation requires a reassessment of the needs of existing purposes, and where changes are found desirable both legal and operational arrangements may have to be modified.

A third role of the Corps in conjunctive use is to make surface waters available by modifying existing reservoir operating criteria. The amount and rate of reservoir release affects both the supply available downstream and the storage available in the reservoir. Development or modification of operating criteria offers the opportunity to increase the amount of water available for supply and effect when it is available. Timing is especially important where water is used for groundwater recharge as well as for providing a direct surface supply. Water which cannot be applied must be stored.

Studies related to conjunctive use have been conducted and authorized by the Corps. One such example is the Phoenix Urban Study. A technical appendix of this study describes a plan of study for a demonstration recharge project in the Salt River Valley. (US Army Engineer District, Los Angeles, 1979) The study covers the technical, environmental, legal, institutional, and economic aspects of groundwater recharge. This study is designed as part of a conjunctive management program for Arizona. Other Corps studies have discussed conjunctive use especially in the context of wastewater disposal (Northeastern United States Water Supply Study, 1972, 73; Merrimack Wastewater Management Study, 1974).

The Corps role in conjunctive use can range from planning investigations to the actual development of supply through new facilities or modifications to existing facilities. The task is not only an engineering one but covers the full range of legal, economic, environmental and institutional considerations.

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SELECTED CONJUNCTIVE USE SYSTEMS

Introduction

To illustrate the variety of ways surface and groundwater are used conjunctively, eight systems have been selected from across the United States. These systems are summarized in Table 1. Most systems use water from two sources, surface and groundwater, but do not manage the resources through an exchange between the surface and groundwater reservoirs. In these examples, the distribution is managed conjunctively rather than the source. The Santa Clara Valley system does manage both surface and groundwater as a resource and water is exchanged between the two reservoirs. Water is also exchanged in the Albuquerque system, where imported streamflow flowing down the Rio Grande infiltrates and recharges the groundwater aquifer. Taken all together, these examples illustrate the many ways of conjunctive management.

TABLE 1

SUMMARY OF SELECTED CONJUNCTIVE USE SYSTEMS

LOCATION	USE	SOURCES	PURPOSES
Albuquerque, NM	Municipal	Groundwater, imported surface water	Meet water rights
Tacoma, WA	Municipal	Groundwater, surface water	Improve water quality
Sacramento, CA	Municipal	Groundwater, surface water	Increase quantity
Phoenix, AZ	Municipal	Groundwater, surface water	Increase quantity Improve reliability
Santa Clara, CA	Municipal Agricultural	Groundwater, surface water, imported surface-water	Increase quantity Artificial recharge
Portsmouth, NH	Municipal	Groundwater, surface water	Increase quantity
Long Island, NY	Municipal	Groundwater, reclaimed water	Artificial recharge
Tri-County, NE	Agricultural	Groundwater, imported surface water	Increase quantity Improve reliability

Albuquerque, New Mexico

The city of Albuquerque uses water conjunctively by augmenting river flows to compensate for groundwater pumping (Bonem, 1976). Albuquerque is located in central New Mexico along the main stem of the Rio Grande (Figure 1). Agricultural water supply is withdrawn mainly from the Rio Grande River, and municipal and industrial supplies are obtained from the extensive groundwater aquifer underlying the valley area. Because the Rio Grande flows over the aquifer, a hydraulic interconnection occurs. This interconnection allows the seepage of streamflow to recharge the aquifer, which then results in decreased surface flow. The amount depends on the hydraulic gradient, the distance from the wells to the river, and time. The time factor is important because the effects of the well pumping are delayed. It may be years before the hydraulic effect of the pumped wells reach the river, but ultimately the amount of flow taken from the river will be 100% of that pumped from the wells. This loss of water from the stream to the aquifer hampers New Mexico's ability to meet its obligations under the Rio Grande Interstate Compact. Under this Compact, the state is required to deliver water to Elephant Butte Reservoir in proportion to the flow measurement each year at Otowi Bridge Gage in Northern Santa Fe County above Albuquerque. To meet this obligation, the State Engineer requires that for any flow reduction on the Rio Grande there must be an accompanying transfer of water rights to offset the actual flow effect. The city of Albuquerque obtained water rights for part of the U. S. Bureau of Reclamation's San Juan-Chama Project water. The San Juan-Chama Project water diverts water from the Rio Blanco, Navajo, and Little Navajo Rivers. These originate in the southwest Colorado Mountains and are tributaries of the San Juan River, which in turn flows into the Colorado River. Using a system of dams, tunnels, and channels, the project moves the water through the Continental Divide and into the Heron Reservoir at Willow Creek in northern New Mexico. Albuquerque gets almost half the diverted water, and the rest is shared by assorted New Mexico towns and irrigation districts. Although the city has not had to start using this water for river augmentation because it has not exceeded its water rights, it will be available in the future when the effects of the well pumping reach the river. As a conjunctive use system, Albuquerque uses augmented surface flows to compensate for a depletion of water caused by pumping of groundwater.

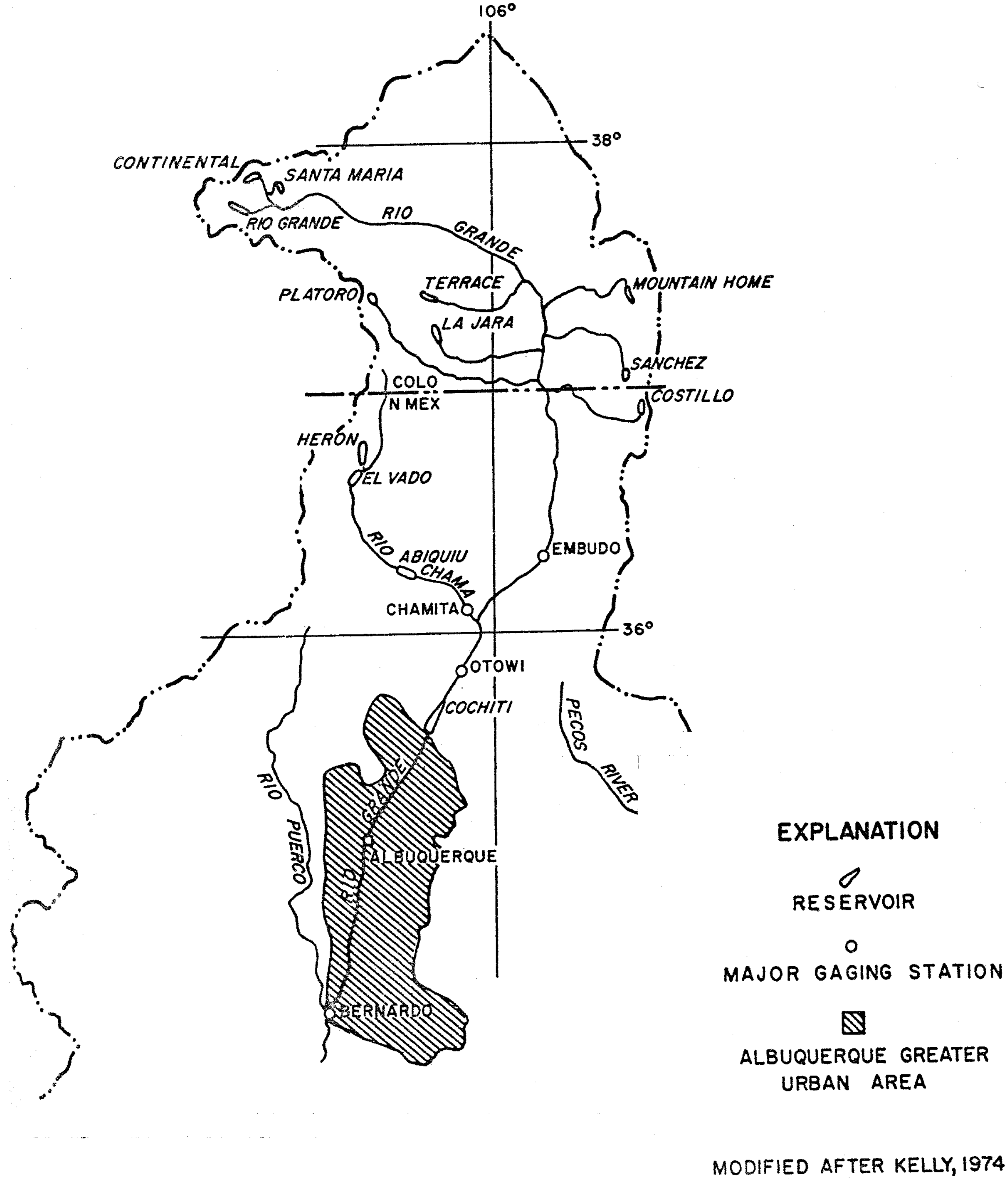

Figure 1. Upper Rio Grande Drainage System, (Bonem, 1976)

Tacoma, Washington.

Tacoma's principal water source is the Green River (Roller, 1978). Part of the time, the river water requires no sedimentation, clarification, or filtration. However, in the late winter and early spring months, a condition of excess turbidity occurs. During this period, suspended material, consisting mostly of colloidal clay, becomes too fine to settle out. At such times, the city augments the Green River supply with groundwater, hence the conjunctive use nature of the system. In the past, this was accomplished using a system of wells and one spring within the Tacoma service area. Now the city has installed the North Fork Well Development which will mostly replace the old well source and insure a continuing supply of high quality water.

The North Fork Well field is located about seven miles upstream from the headwaters, in the North Fork Valley of the Green River Watershed (Figure 2). Water from the North Fork Wells is moved through underground concrete pipe to a storage tank located at the headwater. When turbidity occurs in the Green River, the river water is blended with well water from the storage tank to reduce turbidity to acceptable limits. The water blending operation is controlled by two upstream turbidometers that continuously sample the river. Communications between the automated components of the pumping and blending system are controlled by a solar-powered microwave relay station. When water from the storage tank is injected into the system on signal from the turbidity sensors, it will hydraulically block some or all of the river water depending on how many blending valves are opened. When river turbidity is too high for blending, the entire supply can be drawn from the well field. This water supply configuration is an excellent example of conjunctive use using a divided water system. Water is obtained from both surface and groundwater. These sources are then used together to get the desired quality needed for urban purposes. By using the strategy of conjunctive use, the city of Tacoma can overcome its water-quality problem, and insure a continuing supply of quality water.

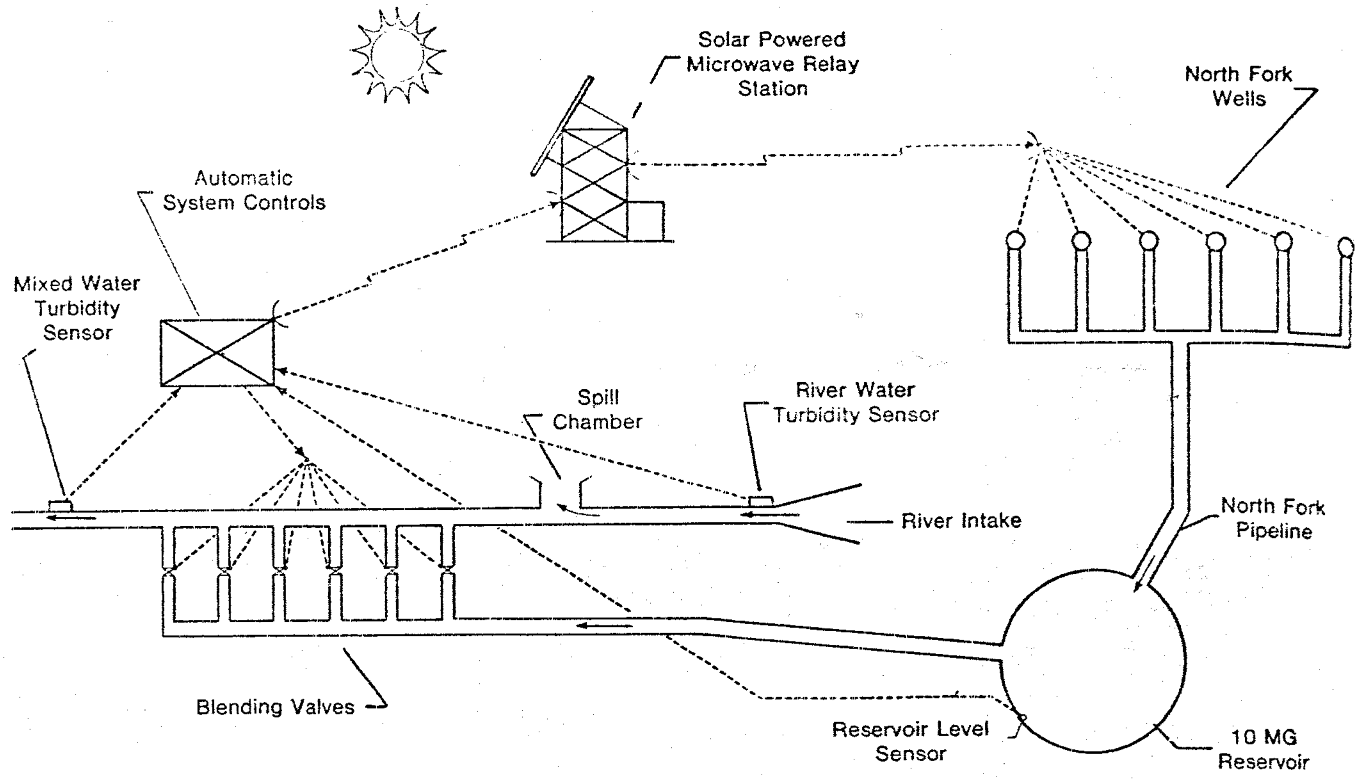

Figure 2. Tacoma Water Supply System, (Roller, 1978).

Sacramento, California.

The city of Sacramento uses a conjunctive use system to meet water supply needs for municipal use (City of Sacramento, 1982). In 1940, when the water supply was largely from the Sacramento River, the city first began developing wells to serve areas which could not easily be served by the river source (Figure 3). As the city grew, it soon became apparent that water requirements could not be met with the existing river water supply capacity. However, because of the generally inferior quality of well water in the area and the superior quality of water in the American River, it was decided that a large, expandable water treatment plant should be constructed on the banks of the American River, rather than develop more wells or expand the existing Sacramento River Water Treatment Plant.

Today, the city receives its water from both the Sacramento and American Rivers, and from groundwater wells. The water from both rivers is treated in three water treatment facilities located throughout the city: Sacramento River, American River, and Riverside. The water from these treatment facilities is distributed for municipal use in the part of the city located south of the Amercian River. In the future, the city plans to phase out the water derived from the wells because of its inferior quality.

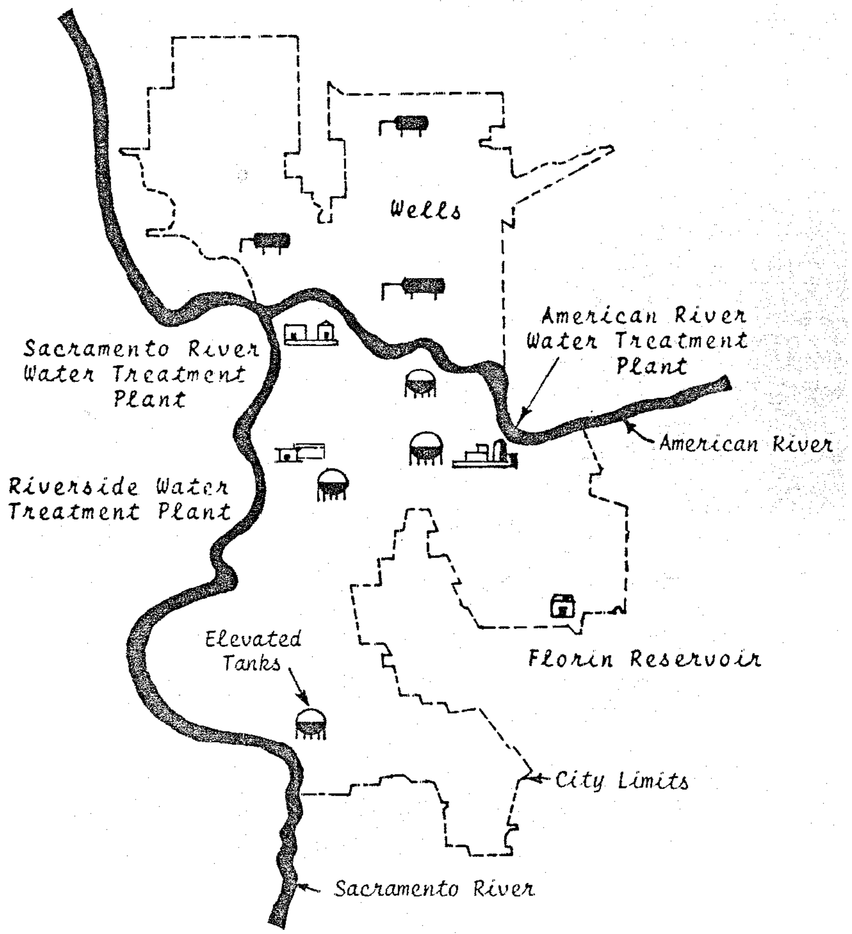

Figure 3. Sacramento Water Service Area, (City of Sacramento, 1982).

Phoenix, Arizona.

In 1940, the city of Phoenix first started using a conjunctive use system to meet municipal needs (City of Phoenix 1981). Prior to this time, the city received all its water from surface sources. Phoenix is located in the Salt River drainage area (Figure 4). Except during infrequent flood periods, no water flows in the Salt River channel in the Phoenix area. The reason for this is that large storage dams have been constructed on both the Salt River and its main tributary, the Verde River, for the purpose of storing irrigation waters. The stored water is diverted about twenty miles east of Phoenix into two large irrigation canals, one of which runs on the north side and the other on the south side of the Salt River Valley. To obtain surface water from this source, the city constructed an infiltration gallery on the Verde River just upstream from its confluence with the Salt River. This water was then transported to the city through thirty miles of large diameter pipe. In later years, the amount of water was increased by the addition of shallow wells alongside the river and a number of large reservoirs to take care of hourly demand. The city of Phoenix decided to establish a conjunctive use system because of the need to increase water supply and to improve the reliability of the system by using another source. Therefore, along with water from the Verde River, the city started receiving groundwater pumped from deep wells located in an area twelve miles to the east.

As the city population increased, the conjunctive use system was expanded. Today, the city of Phoenix is supplied by multiple sources. They receive water from the Verde River through the use of an infiltration gallery and 13 shallow wells. They have four large water treatment plants, Deer Valley, Verde, Squaw Peak, and Valley Vista, which filter water from both the Verde and Salt Rivers. They also have 114 wells located in the Phoenix, Deer Valley, Paradise Valley, and Scottsdale areas. Water from all these sources is fed into lines and distributed throughout the city. In the future, Phoenix plans to continue using a conjunctive use system to meet their water needs.

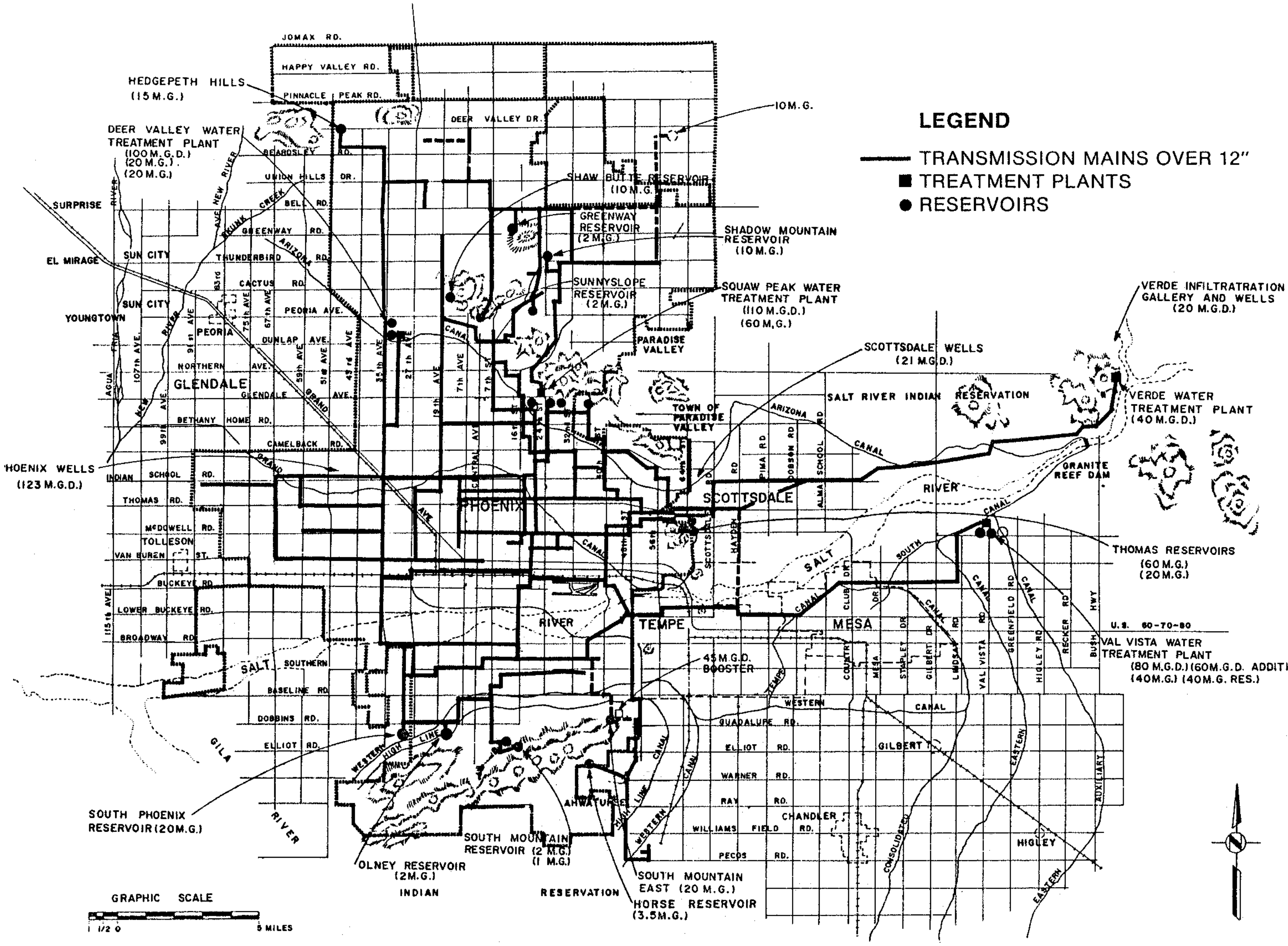

Figure 4. Phoenix Water Supply System, (City of Phoenix, 1981).

Santa Clara, California.

The Santa Clara Valley Water District uses a conjunctive use system (Santa Clara, 1977; Fowler, 1979) to meet both municipal and agricultural needs for the Santa Clara Valley (Figure 5). During the 1900's, when valley use was mainly agricultural, the water supply was from groundwater. Between 1917 and 1934, a drought occured which resulted in a rapid decline of the groundwater table elevation. After the drought, a number of surface water reservoirs were built to hold back the winter floodwater. This water was later released to recharge the groundwater aquifer. The recharge was accomplished through the use of both offstream recharge basins and natural stream channels. Through the conjunctive use of both surface water and groundwater, the Santa Clara Valley Water District was able to continue withdrawing groundwater without a further lowering of the water table.

The addition of the reservoirs added to the available water supply, but it did not increase the limits of the local supply. Because of the physical characteristics of the groundwater aquifer, it can only accept or deliver a limited amount of water. As the valley became increasingly urbanized, water needs exceeded the groundwater basin's capacity, and water supplies from outside the area where imported. Water from the Hetch Hetchy Aqueduct of the city of San Francisco was first used in the Santa Clara Valley in 1962. Water imported through the South Bay Aqueduct of the State Water Project became available in 1965. This water is transported from the Sacramento-San Joaquin Delta. Part of the State Project water is also used for groundwater recharge. The Santa Clara Valley Water District uses the concept of conjunctive use in two ways. It uses both local and imported surface water combined with groundwater to meet its water needs.

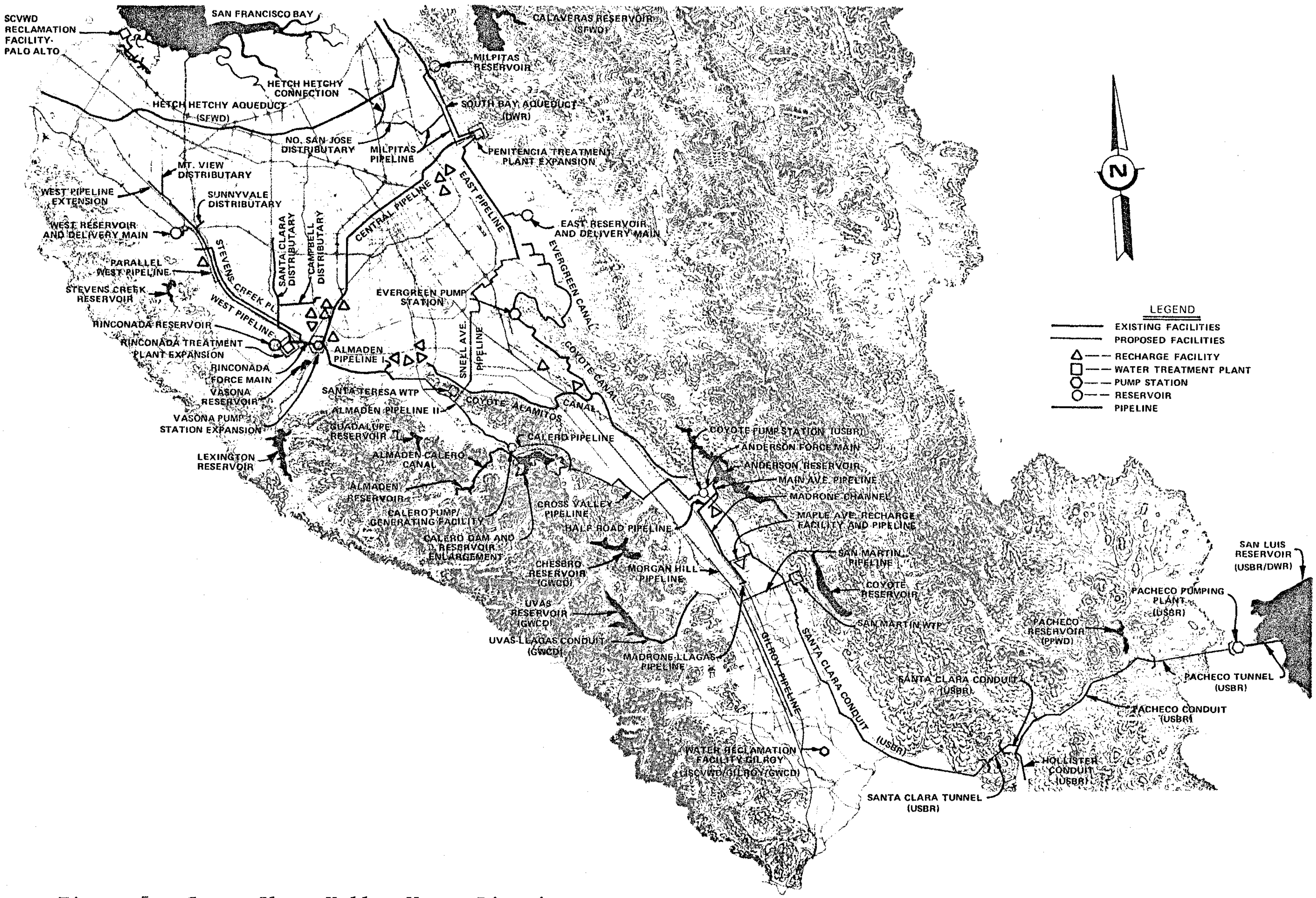

Figure 5. Santa Clara Valley Water District, (Santa Clara, 1977).

Portsmouth, New Hampshire.

The city of Portsmouth uses a conjunctive use system to meet its municipal needs (City of Portsmouth, 1977). In the past, the city had received all its water supply from groundwater. In 1959, part of the well system was lost to development at the Pease Air Force Base. To compensate for the loss, a dam and reservoir were constructed for the city. The reservoir, located in the town of Madbury, stores water from the Bellamy River.

Today, the city receives water from both groundwater and surface water sources (Figure 6). Its principal source is surface water from the reservoir located on the Bellamy River. Water from the reservoir travels by gravity four miles to a treatment plant. At the treatment plant, the necessary purification chemicals are added, and the water is filtered prior to its journey to Portsmouth. Also located at the treatment plant are four gravel pack wells. After treatment, the water is transported to the city for further distribution. In addition to the water supplied from Madbury, the city also has three other sources of water. Located at the Sherburne pumping station are a series of 35 pipes, which are driven to various depths. Water from the well field is pumped into the water supply system by the use of a vacuum. Also serving the city are the Greenland Well and Portsmouth Well #1. In the future, the city plans to expand the conjunctive use system to provide for additional water needs, and to provide for a more adequate supply during periods of drought.

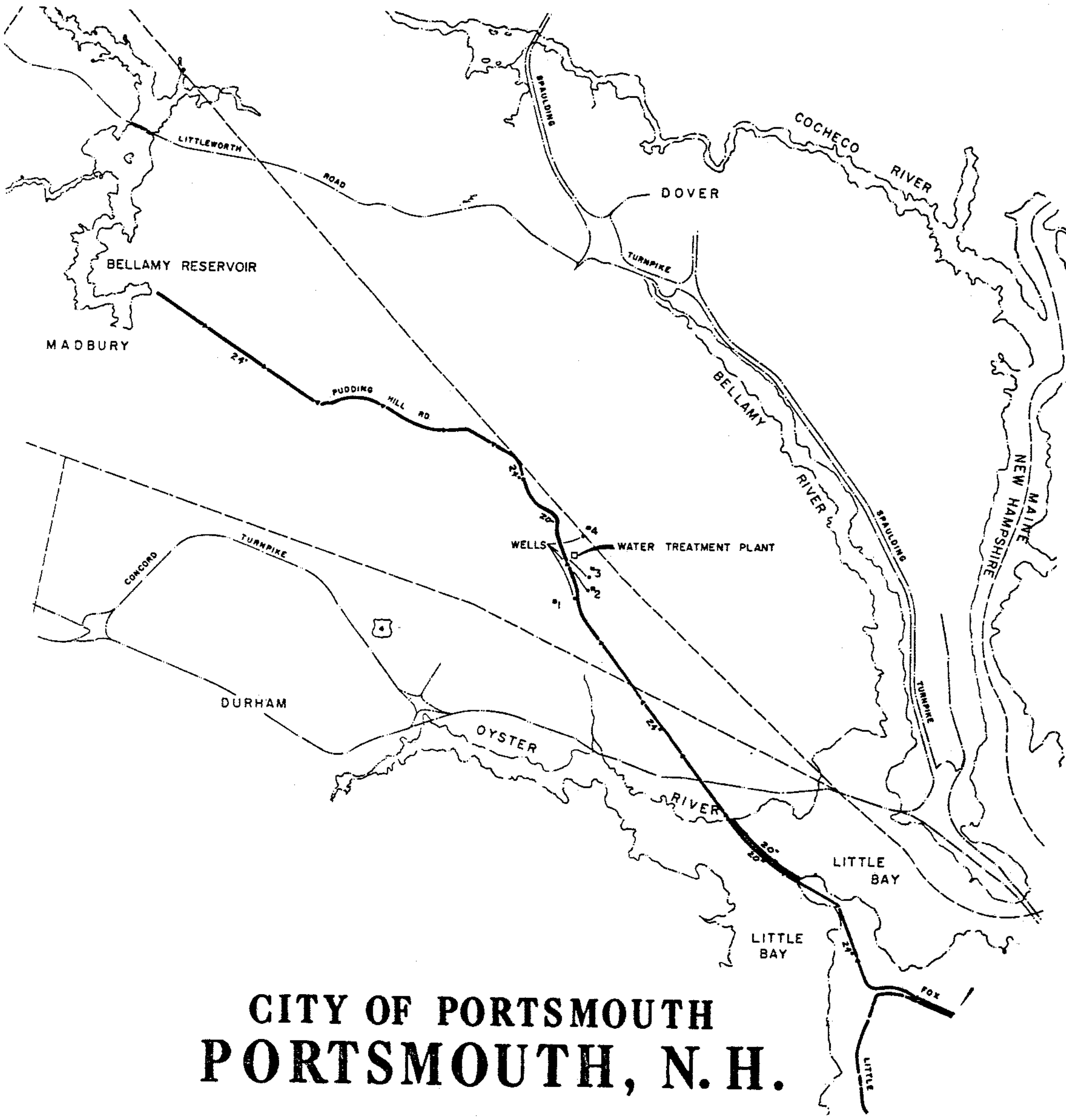

Figure 6. Portsmouth Water Supply System, (City of Portsmouth, 1977).

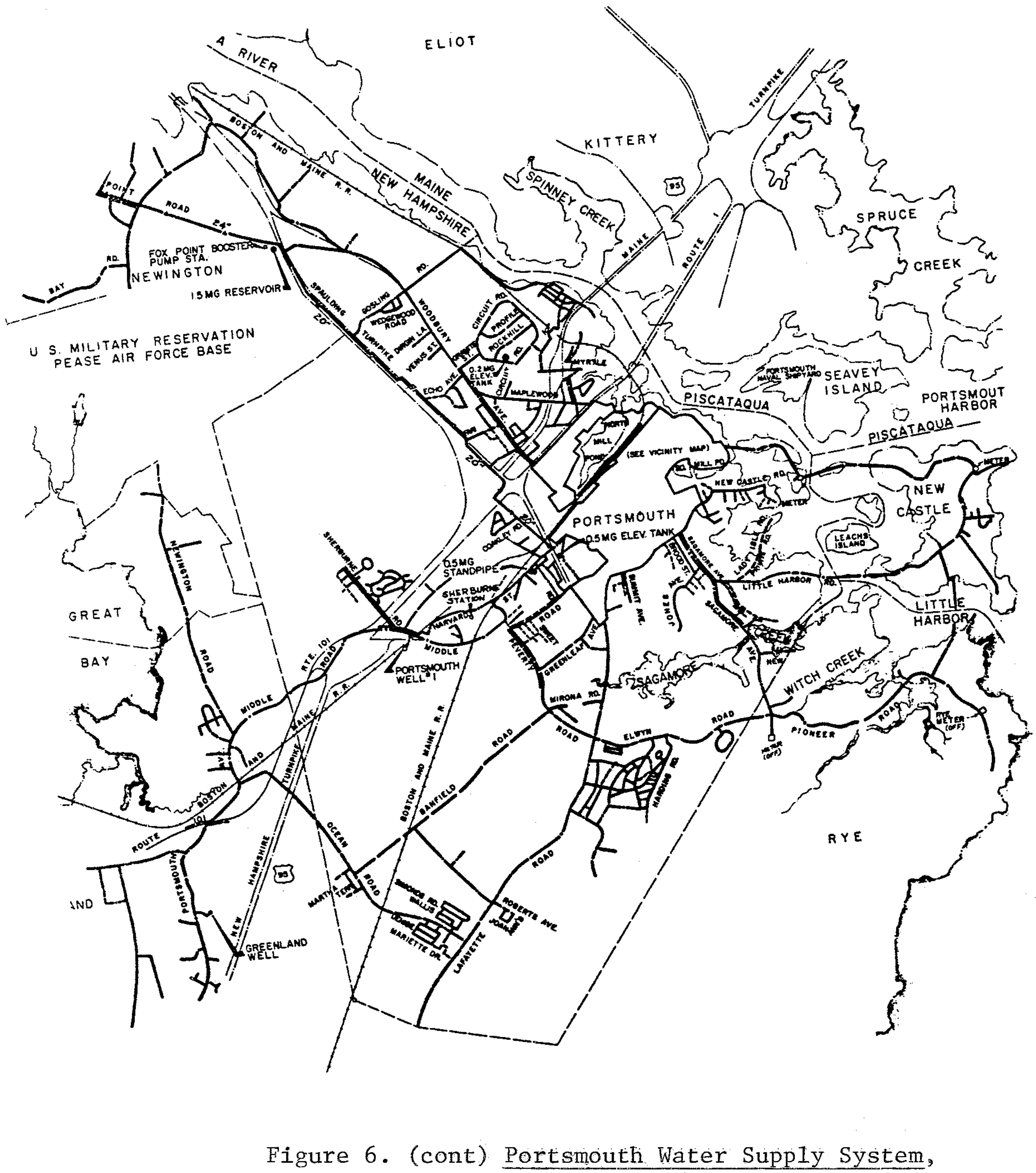

Figure 6. (cont) Portsmouth Water Supply System, (City of Portsmouth, 1977)

Long Island, New York

Long Island has had a long history of conjunctive use (Heath, 1966). The island is underlain by an extensive groundwater table which is hydraulically connected with water from the ocean. Under natural or predevelopment conditions, the hydraulic system was in equilibrium, with long term average groundwater recharge and discharge being equal. When the first European settlers arrived, they dug individual wells for their personal use. The settlers returned this water, back to the groundwater aquifer, by the use of cesspools. This type of conjunctive use system kept the settlers from depleting their natural water supply, and it provided a convenient way to dispose of their wastes. When the population increased in certain areas, the individual wells were abandoned, and public wells were installed. The individual cesspools, however, were retained and little water was lost from the system during use. Although a considerable amount of groundwater was being withdrawn at this time, the system stayed in balance because practically all of the water was returned.

However, as parts of Long Island became increasingly urbanized, pollution of the groundwater started to occur in the vicinity of the cesspools. As the pollution spread, some shallow public wells were replaced with deep wells. Most of the water withdrawn from the deeper units was returned to shallow groundwater areas by means of cesspools, but this water was subsequently discharged to the sea by subsurface outflow or by seepage to streams. In some areas where the water contamination became so severe, large-scale sewer systems were installed. Most of the pumped groundwater that previously had been returned to the groundwater reservoir by means of cesspools was now discharged to the sea through sewers. The net effect of these actions was a rapid lowering of the groundwater table. This decrease in available supply caused an infusion of salt water into the aquifer and contamination occurred. Because of the deteriorating quality of the groundwater, the importation of surface water to the densely populated areas of the island was begun.

Today, Long Island has many different types of water supply systems (Figure 7). In the more populated western section of the island, water is received from surface sources and sewer systems are in use. Because groundwater pumpage is negligible, the groundwater system is largely in balance. In the central section of the island, the water supply is derived from deep wells, and the area is almost completely sewered. This section is experiencing extensive groundwater overdraft, and salt water intrusion is occurring. It is in the rural areas of eastern Long Island, that the conjunctive use system of individual wells and cesspools is still in use. By using water conjunctively, this area is preserving the quantity and quality of their natural water supply.

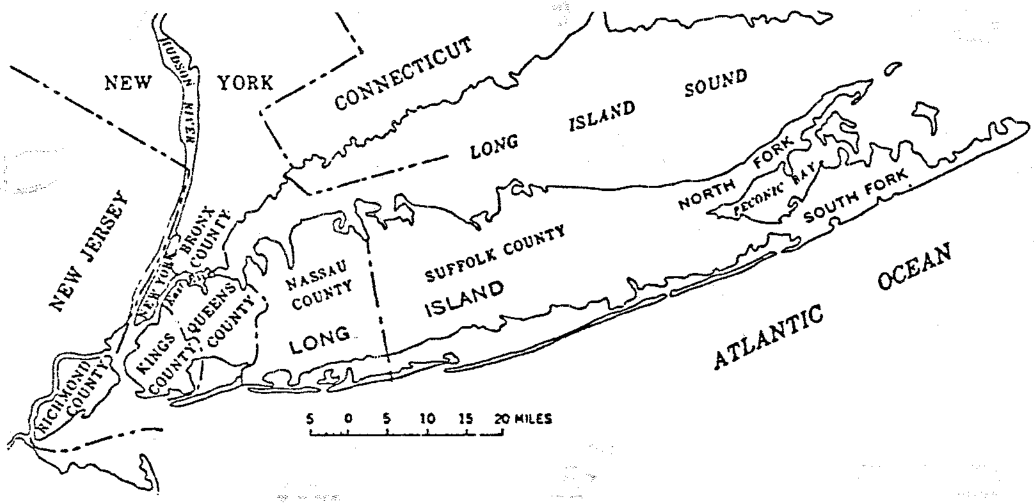

Figure 7. Long Island, New York, (Heath, 1966).

Tri-County, Nebraska.

Farmers, located in the Tri-County area of Gosper, Phelps, and Kearney, irrigate their land by using a conjunctive use system (Central Nebraska Public Power and Irrigation District, 1962). The farmers main source of supply is surface water delivered by the Central Nebraska Public Power and Irrigation District. The Central Nebraska District supplies water for irrigation from a system of structures located on the North Platte River (Figure 8). The principal properties of this system consist of Kingsley Dam and Lake McConaughy north of Ogallala; a diversion dam near North Platte; a 75.6 mile supply canal on which are 26 lakes and three hydropower plants; and 120 miles of irrigation canals. The system provides water for irrigation, electric power generation, flood protection, and recreation.

Before the project was built, most farmers received water for irrigation from their own wells or on-river irrigation from the Platte River. Because the river only provided seasonal flow, irrigation ditches were dry during the seasons when the water was needed the most. Through construction of the Tri-County Project, the Platte River was harnessed, and a steady source of supply became available. Many farmers who receive surface water from the project kept their individual wells, and now use both surface and groundwater sources. By using water conjunctively, the farmers have increased the quantity and improved the reliability of their water supply systems. Other farmers in the area, who irrigate solely with groundwater, also participate in this conjunctive use system. Because the Tri-County Project was constructed in sandy soils, natural recharge occurs through the streambed and gravity irrigation canals. Therefore farmers who use the groundwater are actually receiving surface water from the project. The construction of the Tri-County Project has helped farmers who use surface water or groundwater to manage water conjunctively by providing a surface source and water for artificial recharge.

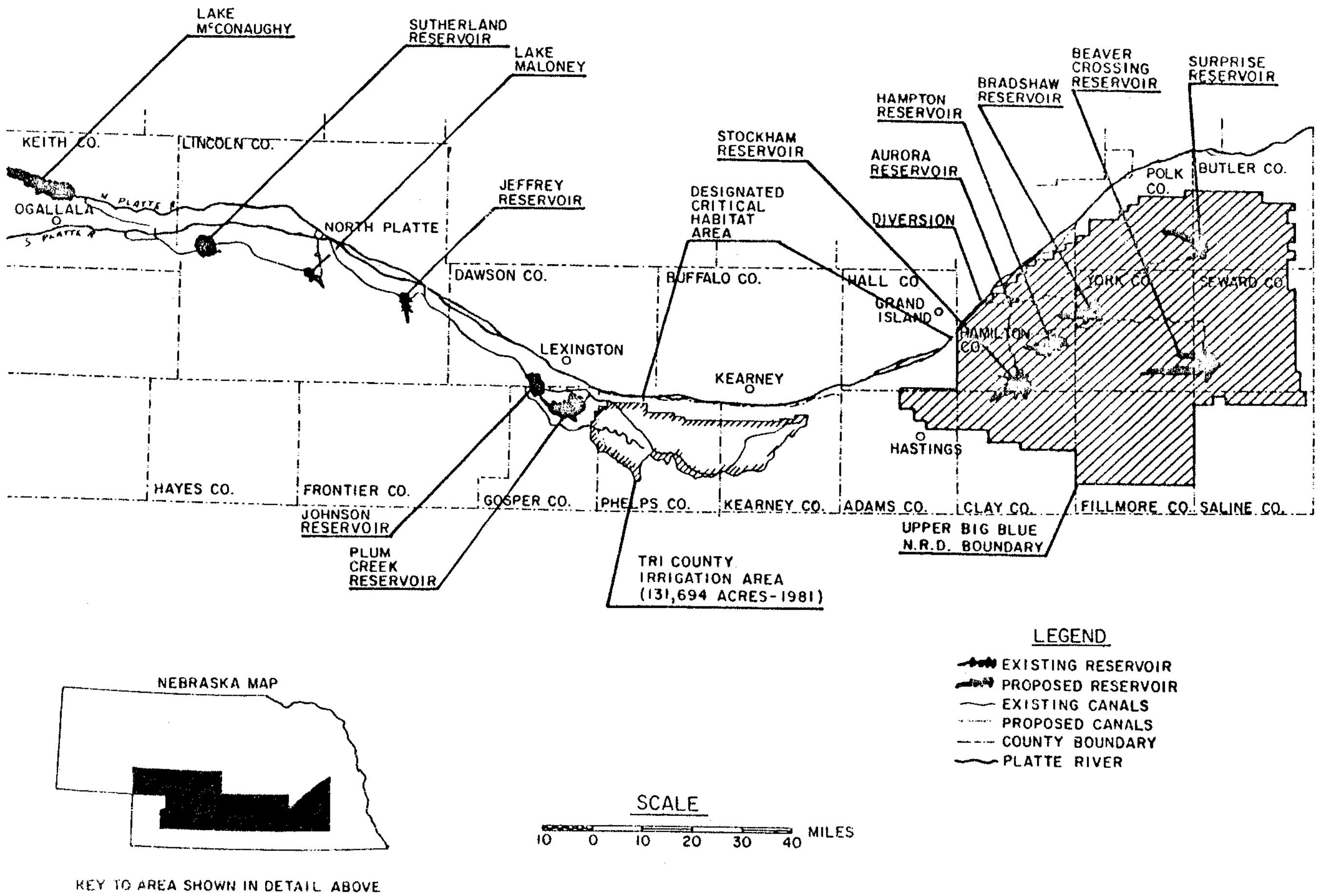

Figure 8. Tri-County Project, (Central Nebraska Public Power and Irrigation District, 1962).

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SELECTED ARTIFICIAL RECHARGE SITES

National Artifical Recharge Activity.

Artificial recharge is of concern in much of the United States. Recharge activity is greatest in Arizona, California, and the Plains States overlying the Ogallala aquifer. Depletion of the Ogallala has led to problems (increased pumping costs, for example) which threaten the economic futures of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, and Texas. A bill recently introduced in Congress proposes to allocate funds to aid in artificial recharge studies and demonstration projects in the Plains states (U.S. Congress, April 28, 1982). Figure 9 shows the location of sites of artificial recharge activity throughout the United States. Table 2 provides a brief description and reference for each numbered site. The references may be found in the Bibliography at the end of this document.

Artificial recharge activity includes feasibility studies, experiments, demonstration projects, and actual systems in operation. Currently, feasibility studies, experiments, and demonstration projects occupy most recharge efforts. While artificial recharge technology is well developed, and the incentive to implement that technology is strong in much of the nation, the need to develop economically and physically feasible recharge schemes has delayed construction of full-scale recharge projects. Geohydrology studies, cost-benefit analyses, and environmental impact reports still must be undertaken in many areas where recharge is considered necessary. Relatively few systems are in operation which provide significant recharge to aquifers. Several of these are located in California. To illustrate the nature of artificial recharge sites several sites have been selected and are briefly described. These are listed in Table 3 and presented on subsequent pages.

Figure 9. NATIONAL ARTIFICIAL RECHARGE ACTIVITY
(Studies, Experiments, Demonstration Projects, Operations). See Table 2.

TABLE 2

NATIONAL ARTIFICIAL RECHARGE ACTIVITY
(Studies, Experiments, Demonstration Projects, Operations)

Alaska

1. Anchorage - Experiments with spreading basins allowing infiltration of diverted creek water (Anderson, 1977).

Arizona

2. Lower Oak Creek Basin - Study of recharge potential of stock tanks capturing storm water runoff (Agenbroad et al., 1981).

3. Flushing Meadows, Phoenix - Pilot project to study feasibility of renovating secondary effluent with spreading basins (Pettyjohn, 1981).

4. Phoenix - Urban study, by the Corps of Engineers, to explore potential recharge (Dixon, August 31, 1982).

5. Salt River - Study of potential for recharge (Wilson, August 25, 1982).

6. Gila Bend - Debris pool of Painted Rock Reservoir released for artificial recharge through basins (U.S. Army Corps of Engineers, South Pacific Division, July 19, 1982).

7. Superior - Study of management considerations for artificial recharge along Queen Creek (Wilson, August 25, 1982).

8. Tucson - Experimental study with pit recharge (O'Donnell et al., July, 1976).

9. Tucson - Urban study, by the Corps of Engineers, to explore potential for recharge (Dixon, August 31, 1982).

Arkansas

10. Arkansas County - Experimental recharge with injection wells to rejuvenate aquifer, discontinued 1969 (International Association of Scientific Hydrology, 1970).

11. Newport - Disposal of groundwater, pumped for cooling system, through injection wells (International Association of Scientific Hydrology, 1970).

12. Fayetteville - Study of potential methods of artificial recharge in the Grand Prairie (Griffis, August, 1976).

Table 2 (continued)

California

13. Butte Valley (California Water Atlas, 1979)

14. Santa Clara Valley (California Water Atlas, 1979)

15. Livermore (California Water Atlas, 1979)

16. Gilroy - Hollister Valley (California Water Atlas, 1979)

17. Salinas Valley (California Water Atlas, 1979)

18. Santa Maria Valley (California Water Atlas, 1979)

19. San Juaquin Valley (California Water Atlas, 1979)

20. Santa Clara River Valley (California Water Atlas, 1979)

21. San Fernando Valley (California Water Atlas, 1979)

22. Los Angeles Coastal Plain (California Water Atlas, 1979)

23. San Gabriel Valley (California Water Atlas, 1979)

24. Orange County Coastal Plain (California Water Atlas, 1979)

25. Upper Santa Ana Valley (California Water Atlas, 1979)

26. San Jacinto Basin (California Water Atlas, 1979)

Colorado

27. Brush - Recharge of irrigation water, during non-irrigation seasons, through pits (Simpson, September 2, 1982).

28. Denver - Study of potential recharge methods for the South Platte River Basin (Swain and Weston, June, 1979).

29. Fort Morgan - Recharge of irrigation water, during non-irrigation seasons, through pits (Simpson, September 2, 1982).

30. Fort Garland - Recharge of irrigation water, during non-irrigation seasons, through pits (Simpson, September 2, 1982).

31. Morgan County - Proposed artificial recharge project diverting water from the South Platte River (Burns, July, 1980).

32. Prewitt - Recharge of irrigation water, during non-irrigation seasons, through pits (Simpson, September 2, 1982).

Table 2 (continued)

33. Sterling - Recharge of wastewater effluent during winter months (Simpson, September 2, 1982).

34. El Paso County - Tests with recharge pits in Upper Squirrel Creek Basin (Emmons, July, 1977).

Delaware

35. New Castle County - Possibility of a large-scale artificial groundwater recharge project to insure adequate water supply discussed (University City Science Institute, March 22, 1971).

Florida

36. East Orange County - Experiments and studies connector well to allow water from shallow aquifer to recharge lower Floridian Aquifer (Bush, 1979).

37. Orlando - Recharge through drainage wells (Kimrey, May, 1978).

38. St. Petersburg - Feasibility tests with subsurface injection of storm water runoff through wells (Barr and Hickey, 1979).

39. Gainesville - Study of potential of combining flood control with artificial recharge in Peninsular Florida (Glass et al., September, 1976).

40. Cocoa - Feasibility tests with recharge through injection wells to prevent saltwater intrusion (Tibbals, 1972).

41. Tampa Bay - Experiments to determine optimum method of recharge (Sinclair, 1977).

Hawaii

42. Kahului (Maui) - Recharge of wastewaters through injection wells (Hargis and Peterson, January - February 1974).

43. Hanapepe (Kauai) - Recharge of streamwater through wells (Hargis and Peterson, October, 1970).

44. Island of Hawaii - Recharge of streamwater through wells (Hargis and Peterson, October, 1970).

Idaho

45. Snake River - Proposed project to divert waters from the Snake River for artificial recharge (U.S. Congress, March 11, 1972).

46. Big Lost River - Disposal of low-level aqueous radioactive wastes through injection wells (International Association of Scientific Hydrology, 1970).

Table 2 (continued)

Illinois

47. Peoria - Recharge with pits to prevent decline of groundwater levels (Pettyjohn, 1981).

Kansas

48. Groundwater Management District No. 1 - Pilot recharge site using impoundments (Hargadine, July 28, 1982).

49. Groundwater Management District No. 2 - Pilot recharge site using pit infiltration basin with sedimentation trap (Hargadine, July 28, 1982).

50. Groundwater Management District No. 3 - Several pilot recharge sites using various methods (Hargadine, July 28, 1982).

51. Groundwater Management District No. 4 - Numerous pilot recharge sites using various methods (Hargadine, July 28, 1982).

52. Groundwater Management District No. 5 - Pilot recharge site using channel modification (Hargadine, July 28, 1982).

Louisiana

53. Baton Rouge - Recommendation to institute a program to construct reservoirs for direct water supply and artificial recharge (Adams, August, 1971).

Michigan

54. Kalamazoo - Recharge by induced infiltration to prevent decline of water table (Pettyjohn, 1981).

Minnesota

55. St. Paul - Tests to determine feasibility of recharge with injection wells (Ehrlich et al., 1976).

Nebraska

56. Aurora - Investigation of potential for recharge through injection wells (Kouma, et al., 1979).

57. Little Blue Natural Resources District - Project with recharge of floodwaters under construction (Eisenhauer, August 24, 1982).

58. Lincoln - Economic evaluation of the feasibility of artificial groundwater recharge in Nebraska (Supalla, January, 1981).

59. Tryon - Recharge with stock tanks (Powers, September 2, 1982).

Table 2 (continued)

60. Upper Big Blue Natural Resources District - Proposed project to divert Platte River water for recharge (Upper Big Blue Natural Resources District, 1982).

Nevada

61. Cold Spring Valley - Study to determine feasibility of recharge by injection methods (Campana et al.).

New Jersey

62. Malbaro - Storage of municipal water in a recharge well (Gordon Corner Water Company, August 24, 1982).

63. Wildwood - Injection of freshwater during off-season to meet peak demands during the summer months (Canace, July 28, 1982).

New Mexico

64. Santa Clara Indian Reservation - Artificial aquifer used to retain waters infiltrating from surface (Pettyjohn, 1981).

65. Southern High Plains of New Mexico - Study of potential artificial recharge systems using playa lake water (Brown et al., August, 1978).

New York

66. Bay Park - Recharge by injecting reclaimed waters through wells (Ku et al., 1980).

67. Nassau County - Stormwater basins used for recharge (Aronson and Prill, 1978).

North Dakota

68. Glenburn - Subsurface dam retains groundwater in sand and gravel aquifer (Pettyjohn, 1981).

69. Minot - Injection of river water through shafts (Pettyjohn, 1981).

70. Valley City - Water diverted from river to recharge pit (Pettyjohn, 1981).

Ohio

71. Canton - Recharge with collector well connecting upper and lower aquifers (Pettyjohn, 1981).

72. Dayton - Lagoons and ditches flooded to allow infiltration of diverted river water (Pettyjohn, 1981).

73. Mill Creek Valley - Potential of injection well recharge studied (Fidler, 1970).

Table 2 (continued)

Oklahoma

74. Oklahoma Panhandle - Examination of potential for recharging the Ogallala Aquifer (Bekure and Eidman, March, 1972).

75. Southwest Oklahoma - Recharge to dilute flouride groundwater proposed (Pettyjohn, September 2, 1982).

Oregon

76. Dalles - Minor recharge project, closed down recently (Harris, August 25, 1982).

77. Salem - Tests to determine feasibility of injection well recharge (Foxworthy, 1970).

South Dakota

78. Sioux Falls - Modification of channel diverting waters from a flood control dam (International Survey of Scientific Hydrology, 1970).

Texas

79. Dell Valley - Project under construction to inject impounded floodwaters through wells (Flood Control Plan Recycles Water, April 24, 1981; Logan, Fall 1981).

80. El Paso - Potential for injection - well recharge with treated sewage effluent appraised (Garza, et al., September 1980).

81. High Plains of Texas - Numerous sites where recharge with playa lake water has been attempted and appears to be economically infeasible (International Association of Scientific Hydrology, 1970; Wyatt, July, 1982).

82. Houston - Studies of the feasibility of preventing land subsidence with artificial recharge (Garza, 1977).

83. San Antonio - Proposed project to recharge Edwards Aquifer (Elder et al., October, 1979).

Utah

84. Salt Lake Valley - Recommendation to purchase land and begin studies of potential for artificial recharge (Hansen, 1978).

85. Utah Valley - Potential for artificial recharge to protect and purify water for municipal and industrial uses exists (Carpenter, 1978).

86. Wasatch Aquifer - Potential for artificial recharge along western front of Wasatch Mountains (Wasatch Aquifer Refilling Studied, August 8, 1977).

Table 2 (continued)

Virginia

87. Norfolk - Tests with injection of fresh water into a brackish-water aquifer (Brown and Silvey, 1977).

88. Roanoke - Disposal of stormwater runoff through drainage wells (Breeding, February, 1977).

Washington

89. Walla-Walla - Recharge project no longer in operation (U.S. Geological Survey, August 25, 1982).

Wisconsin

90. Washura County - Demonstration project using an infiltration pond (Novitzki, April, 1976).

TABLE 3

SUMMARY OF SELECTED ARTIFICIAL RECHARGE SITES

LOCATION	FEATURES		
	METHOD	SOURCES	CURRENT STATUS
Orange County, CA	Basins, channel modification, injection wells	Floodwater, imported water, wastewater	System in operation
Dell Valley, TX	Injection wells	Floodwater	System under construction
Sioux Falls, SD	Channel modification	Floodwater	System in operation
Oak Creek Basin, AZ	Detention ponds	Floodwater	Under construction
Los Angeles County, CA	Spreading grounds, unlined channels	Floodwater, reclaimed water, imported waters	System in operation
San Bernadino Valley CA	Spreading grounds	Imported floodwater	System in operation
Blue Basin, NE	Infiltration from flood control reservoirs.	Floodwater	System under construction

Orange County, California.

An extensive recharge scheme in Orange County, California used floodwaters and stormwater runoff to recharge the aquifer underlying the Santa Ana River Basin (Orange County Water District, April, 1982). Floodflows, originating in the flood plain east of Orange County, are impounded by the Corps of Engineers' Prado Flood Control Reservoir, an earthen structure with 196,240 acre feet of storage capacity. Waters leave the dam and flow into the Santa Ana River, where they are routed into multiple recharge facilities covering 1,100 acres of Orange County (Figure 11).

Most recharge takes place in the Santa Ana River area. The Santa Ana River itself has been transformed into a spreading facility by the Orange County Water District. A levee built by the district divides the river in half longitudinally. The western section contains a sequence of spreading basins, each of which fills before allowing water to pass to the next basin downstream. The basins, 200 to 400 feet wide and up to 10 feet deep, can retain great amounts of water and percolate up to 4 vertical feet of water daily. Water not held in the spreading basins weaves through a maze of dikes in the eastern section of the Santa Ana River. These temporary sand structures, often destroyed during heavy storm flow, slow down the river, allowing infiltration of water which otherwise would pass into the Pacific Ocean.

Several off-channel basins provide additional groundwater recharge in Orange County. Anaheim Lake, Warner Basin, Kraemer Basin, Placentia Basin, and Burris Pit, a former sand and gravel site, all retain Santa Ana River runoff for infiltration purposes. Waters imported from the Colorado River and Northern California, by the State Water Project, are also percolated through these basins. While recharge is their chief function, a few of these basins also serve as recreational facilities; Anaheim Lake, is stocked with trout and open for fishing during much of the year.

Orange County's water conservation efforts, which, in addition to recharge by infiltration include wastewater injection systems to prevent sea water intrusion, have been extremely successful. Orange County was able to survive decreased supply from the State Water Project during California's 1975-77 drought. Recharge through on and off-channel basins adds an average of 250,000 acre-feet of water to the area's aquifer annually, helping to meet expanding water needs in the Santa Ana River Basin.

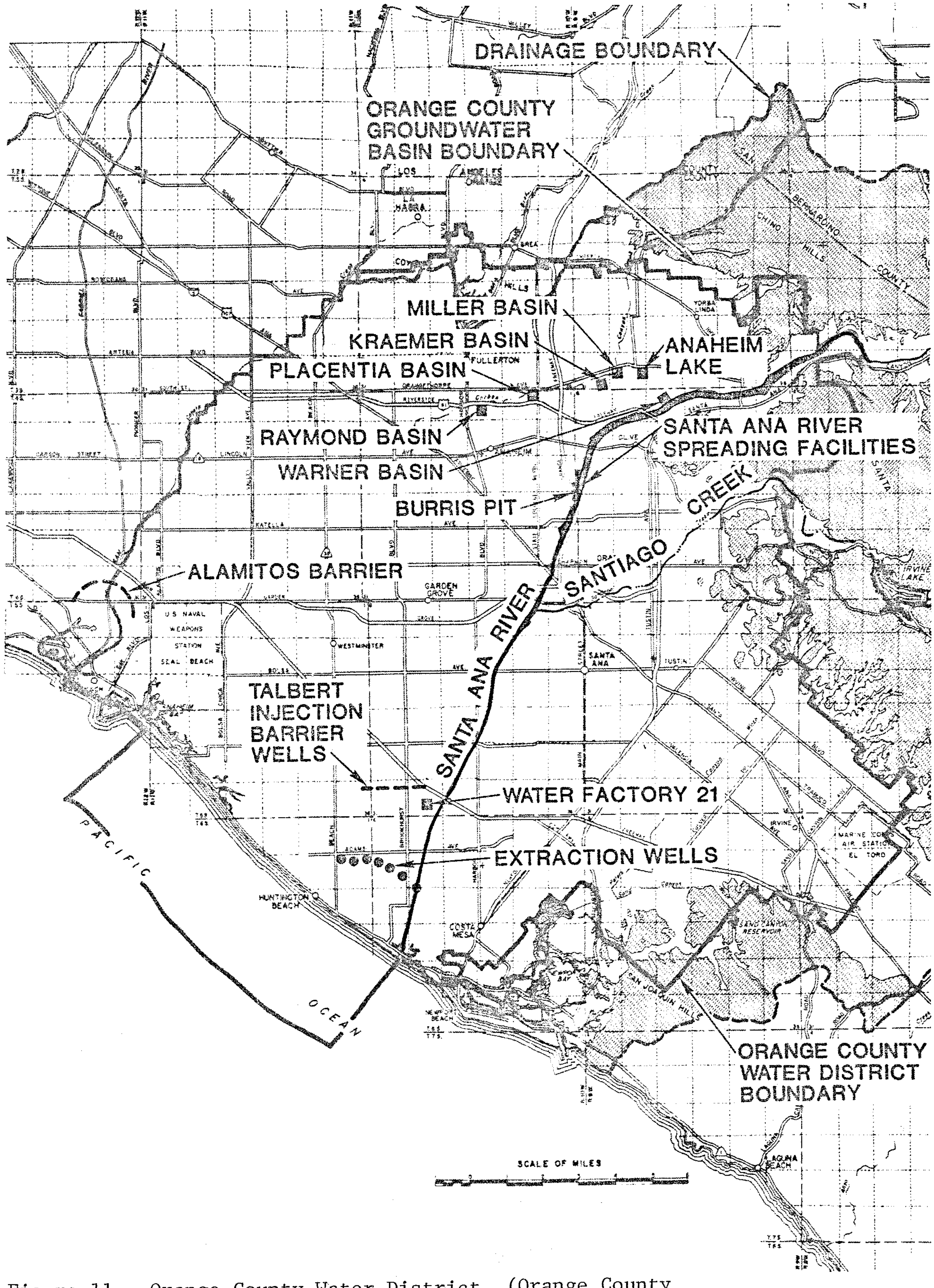

Figure 11. Orange County Water District, (Orange County Water District, 1982).

Dell Valley, Texas.

Groundwater recharge is a secondary purpose of a Soil Conservation Service project planned for the Dell Valley, located along the Texas-New Mexico border, 70 miles east of El Paso (Flood Control Plan Recycles Water, 1980; Logan, 1981). Impounded floodwaters will be injected through wells into the area's Victoria Peak Aquifer. Flows into injection wells and percolation of water stored behind the projects dams will add about 6,000 acre-feet of water to the aquifer annually.

In original project plans, floodwaters, which damage thousands of acres of farmland every year, were to have been impounded behind five earthen dams and then routed through overland pipelines and channels to the valley's dry salt lakes, where most of the water would have evaporated. The cost of constructing channels, some nearly seven miles long, would have rendered the entire project uneconomical. Disposing of the water through injection wells appears to be a viable alternative. In the present plan, impounded floodwaters will exit the dams via spillways, pass through filter fields to screen out sediment, and then flow by gravity into wells grouped 300 to 3,000 feet downstream from each dam (Figures 12 and 13).

The project is in the early construction stage. Only one dam has been built, and injection wells are still being drilled. Wells were sited using a photogeological process. Fracture trace intersections were identified with the aid of aerial photographs; field work subsequently determined optimal well locations. Each well will include a 26 inch diameter surface hole 40 feet into the limestone formation, followed by a 20 inch diameter production hole extending between 1200 and 1400 feet below the surface. The hardness of the rock has made drilling difficult.

When completed, the project, expected to cost $16 million, will significantly enhance the Dell Valley's groundwater-dependent economy, reducing flood damages by 85% and decreasing decline of the water table level by 15% annually. Recharge will also address the area's groundwater quality problems.

Salts percolating from the dry salt lakes and leached from irrigated soils have been polluting the Victoria Peak aquifer. Recharged waters will be of superior quality to the waters already in the aquifer and should decrease the present rate of groundwater quality deterioration.

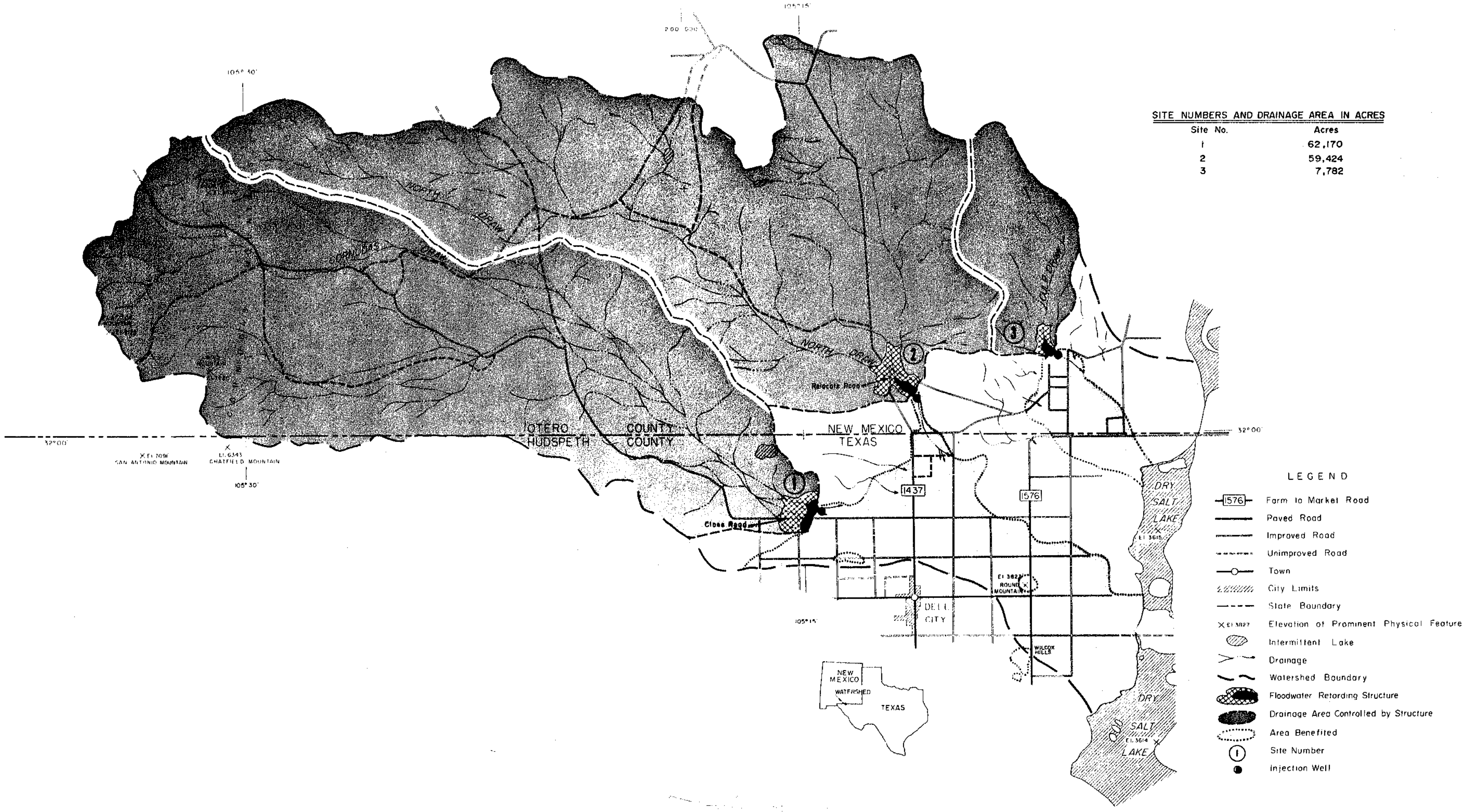

Figure 12. Dell Valley, Texas (Cornudas, North and Culp Draws Watershed) (Flood Control Plan Recycles Water, 1980; Logan, 1981).

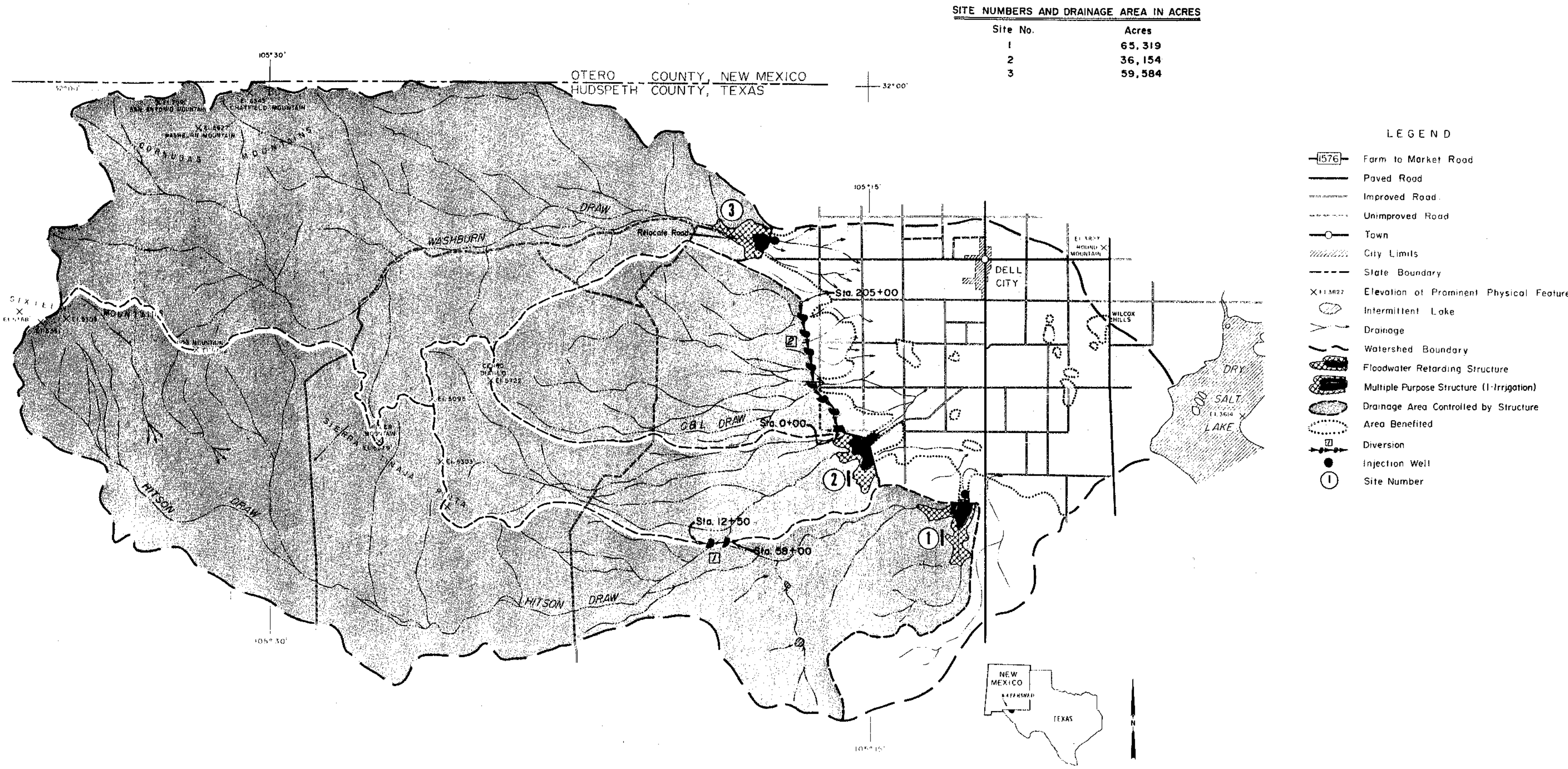

Figure 13. Dell Valley, Texas (Hitson, C & L and Washburn Draws Watershed), (Flood Control Plan Recycles Water, 1980; Logan, 1981).

Sioux Falls, South Dakota.

Artificial recharge with Corps of Engineer's flood control facilities has been practiced successfully in Sioux Falls, South Dakota (International Association of Scientific Hydrology, 1970). The Corps facilities, completed in 1961, include a dam and a diversion channel which provide flood protection for Sioux Falls by diverting floodflows passing through the Big Sioux River (Figure 14). Flooding occurs when heavy rains fall in the Sioux River Valley north of Sioux Falls.

The Corps of Engineers and the City of Sioux Falls Water Department have implemented several measures to induce infiltration of waters entering the diversion channel from the Big Sioux River and from Silver Creek. The Corps has built a self-operating diversion weir along the diversion channel. The weir retains flows up to 2,300 cfs in the first 3,500 feet of the diversion channel, allowing infiltration of waters which otherwise would pass through the rest of the channel and eventually reenter the Big Sioux River. The Corps also operates the floodgates of its dam to insure that water for recharge is provided whenever possible, often closing all ten gates during low-flows of the Big Sioux River. Sedimentation problems are addressed by the City Water Department, which occasionally dredges out the section of the channel between the dam and the weir. Without dredging operations, silts and clays deposited by diverted waters would line the bottom of the channel and inhibit recharge. The city last dredged out the channel in 1976. Because the area's sand and gravel aquifer is Sioux Falls' chief source of water, these artificial recharge efforts are extremely important. Infiltration of diverted water has prevented wells from going dry during years of low rainfall. By maintaining groundwater levels, artificial recharge should allow groundwater to continue to fulfill Sioux Falls' water needs.

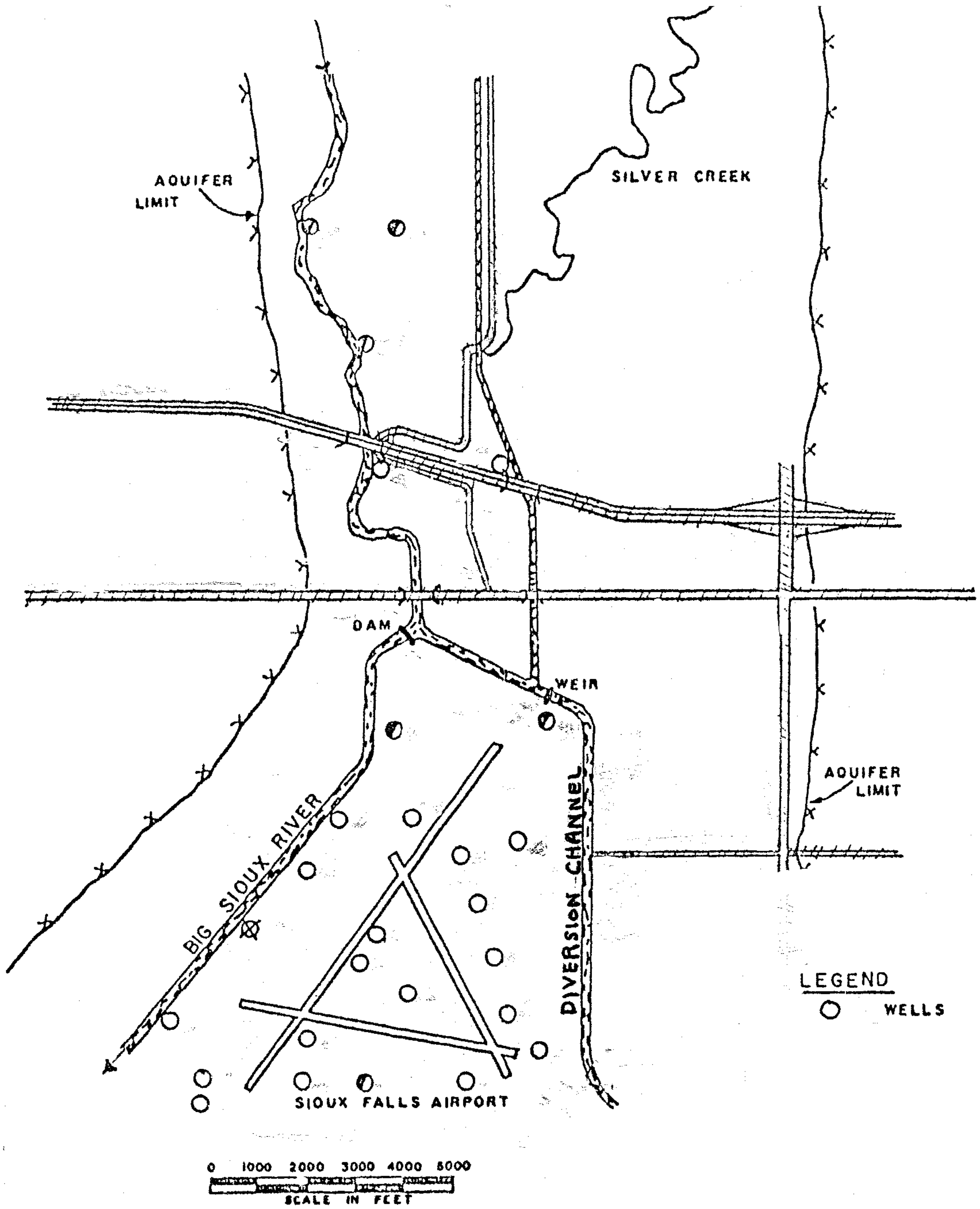

Figure 14. Sioux Falls, South Dakota, (International Association of Scientific Hydrology, 1970).

Oak Creek Basin, Arizona.

Artificial recharge and flood control with small, man-made impoundments could become an important water resources management technique in Northern Arizona and other areas of the arid Southwest (Agenbroad et al., 1981). Stock tanks, or ponds, occupying small drainage areas, collect and retain stormwater runoff, thereby supplying drinking water for cattle. These tanks are constructed and used by private land owners, and vary greatly in shape and size. Storage capacities range from less than one to more than 11 acre-feet. Almost all are lined with clay or bentonite to prevent seepage. Most recharge from these tanks is therefore unintentional and insignificant.

Ongoing investigations of the effect of stock tanks on the hydrology of lower Oak Creek Basin (Figure 15) suggest, however, that more extensive and scientific use of stock tanks for recharge and flood control purposes could prove beneficial. Most of Northern Arizona's 15 inches of annual precipitation falls during a few July and August thundershowers. This stormwater quickly runs out of drainage areas in gullies, allowing little infiltration into the area's highly permeable alluvial soils. Runoff collects in channels and enters the Salt River, creating flood pulses which eventually reach Phoenix. By retaining stormwater runoff, stock tanks can impede flood pulses and diminish downstream damages. A large number of tanks constructed in alluvial soils without lining could also allow a significant amount of infiltration into aquifers. Recharge would greatly benefit agriculture in Northern Arizona, which, in the absence of perennial streams, depends entirely on groundwater for irrigation. Legal considerations might prevent construction of stock tanks for recharge and flood control purposes, as extensive impoundment of runoff could violate water rights of downstream users.

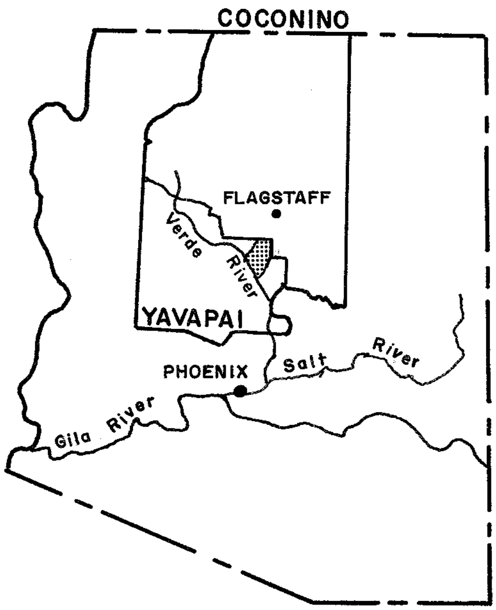

Figure 15. Location of Oak Creek Basin Study Area, (Agenbroad et al., 1981).

Los Angeles County, California.

Flood control and artificial recharge facilities have been coordinated to form a highly efficient water conservation program in Los Angeles County, California (Los Angeles County Flood Control District, June 6, 1977, Rheinhard, May 6, 1982, Sherman, 1977, United Nations, 1975). A network of 19 dams and over 2,000 miles of drainage channels, developed through cooperation between the Los Angeles County Flood Control District and the Corps of Engineers, provides flood protection for the citizens of Los Angeles County. In addition, almost all the storm runoff impounded by these facilities is routed into subsurface reservoirs, where it is stored for municipal, agricultural, and industrial use. Only 5% of the precipitation falling on the watershed upstream from major conservation facilities and only 15% of all rainfall in Los Angeles County reaches the Pacific Ocean each year.

A large portion of the impounded floodwaters is conserved in Los Angeles County's 3,126 acres of spreading grounds, 2,000 of which are owned by the Flood Control District. An annual average of 250,000 AF of water, valued at $20 million, recharges the aquifers underlying Los Angeles County through the District's spreading grounds alone. Since artificial recharge activity first began in 1919, more than 11 million AF of water has been percolated via spreading grounds, in unlined channels, and behind dams and reservoirs.

The largest recharge facility in Los Angeles County is the Rio Hondo Coastal Basin Spreading Grounds, a series of basins paralleling the Rio Hondo River (Figure 16). These basins, along with the San Gabriel River System, retain stormwaters released from Whittier Narrows Dam, a Corps of Engineers flood control project spanning across the Rio Hondo and the San Gabriel Rivers. Flocculents are added to the waters just as they exit the dam to reduce the concentration of sediment in waters diverted to the Rio Hondo and San Gabriel spreading grounds. While outflows from Whittier Narrows Dam are intermittent, recharge of imported and reclaimed water has necessitated year round use of the recharge facilities. Insect problems associated with continuous use of spreading grounds have been limited by battery spreading.

To permit increased use of floodwater for recharge, the Corps of Engineers has altered its outflow schedules for the spillway gates of Whittier Narrows Dam. In the past, the Corps operated the dam's San Gabriel outlets to release waters at 5,250 cfs, a rate far exceeding the 300 cfs intake capacity of the San Gabriel spreading grounds. Any waters building up behind the dam were diverted via a flood flow channel to the Rio Hondo conservation pool. There they would be released through the Rio Hondo outlet gates at rates below the 700 cfs intake capacity of the Rio Hondo spreading grounds. This operating procedure allowed 15,000 AF of water to bypass the spreading grounds and flow into the Pacific Ocean every year. With the recent enlargement of the Rio Hondo conservation pool to 2,500 AF, releases into the San Gabriel and Rio Hondo River can be held at 385 and 700 cfs, respectively. Only when the conservation pool is full are waters released at rates exceeding the intake capacities of the San Gabriel and Rio Hondo spreading grounds. By changing outflow schedules and the size of the Rio Hondo conservation pool, the Corps of Engineers has enabled the Flood Control District to conserve 6,000 AF of releases from Whittier Narrows Dam annually.

Efforts to retain larger quantities of water for artificial recharge are being made throughout Los Angeles County. The potential of utilizing the 100,000 AF/yr. of Los Angeles River water passing into the Pacific Ocean each year has been explored. None of the proposed recharge schemes, which include injecting water through wells adjacent to the river and redirecting water to the Rio Hondo spreading grounds, appears cost-effective at this time. In addition, remedial work on the Flood Control District's dams and reservoirs, which, when completed, will allow increased storage of stormwaters, has already begun. The greatest extension of current conservation efforts will most likely occur through changes in operations of the five Corps of Engineers' dams in Los Angeles County.

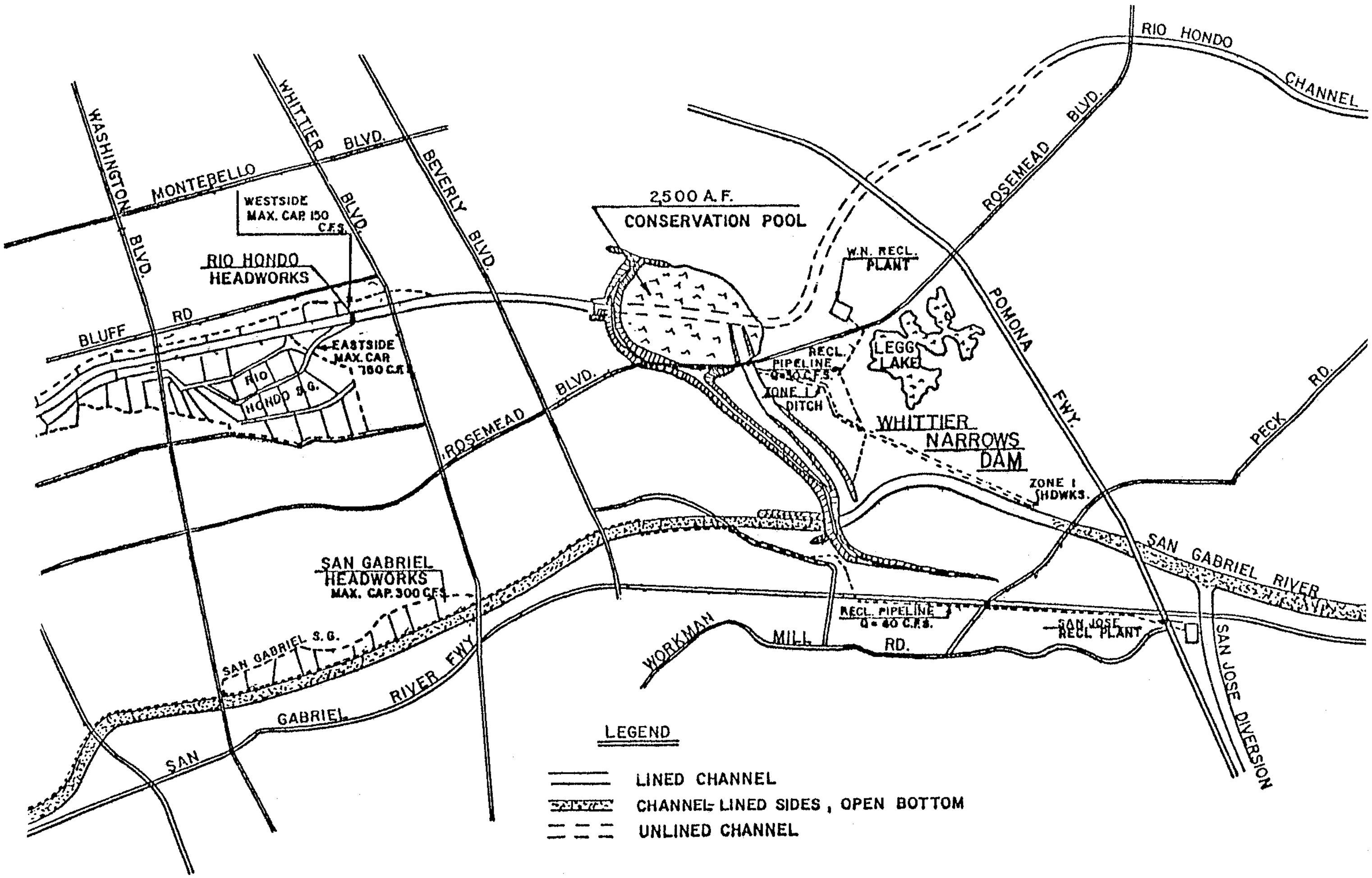

Figure 16. Whittier Narrows Dam/District Recharge Facilities, (Los Angeles County Flood Control District, 1977).

San Bernardino Valley, California.

Floodwaters passing through the State Water Project's California Aqueduct were used in 1978 for recharge in the Mojave River Valley and San Bernardino River Valley (Matusak, 1980). The floodflows originated in the Kern River, and were diverted by the Kern River Intertie to the California Aqueduct before reaching the San Bernardino and Mojave River Valley (Figure 17).

The Kern River Intertie, a Corps of Engineers' flood control project completed in 1977, consists of a sedimentation basin and a gated 3,500 cfs gravity flow connection between the Kern River and the California Aqueduct (U.S. Army Corps of Engineers 1972; U.S. Army Corps of Engineers 1979). Normally, waters diverted from the Kern River would be stored in surface reservoirs throughout Southern California. These facilities, however, were full in 1978 due to local runoff conditions, so waters were routed for two months to spreading grounds in the Mojave River and San Bernardino Valley.

No efforts were made to measure the quantity of water entering the groundwater basins, although project officials estimated that about 22,500 acre-feet were conserved. The project's primary purpose was to explore and evaluate the nature of negotiations and agreements between the California Department of Water Resources and local water agencies necessary to increase conservation of State Water Project waters by artificial recharge. Coordination among the agencies involved was excellent. No long term recharge using State Water Project waters, however, will be implemented in the near future in the San Bernardino or Mojave River Valley.

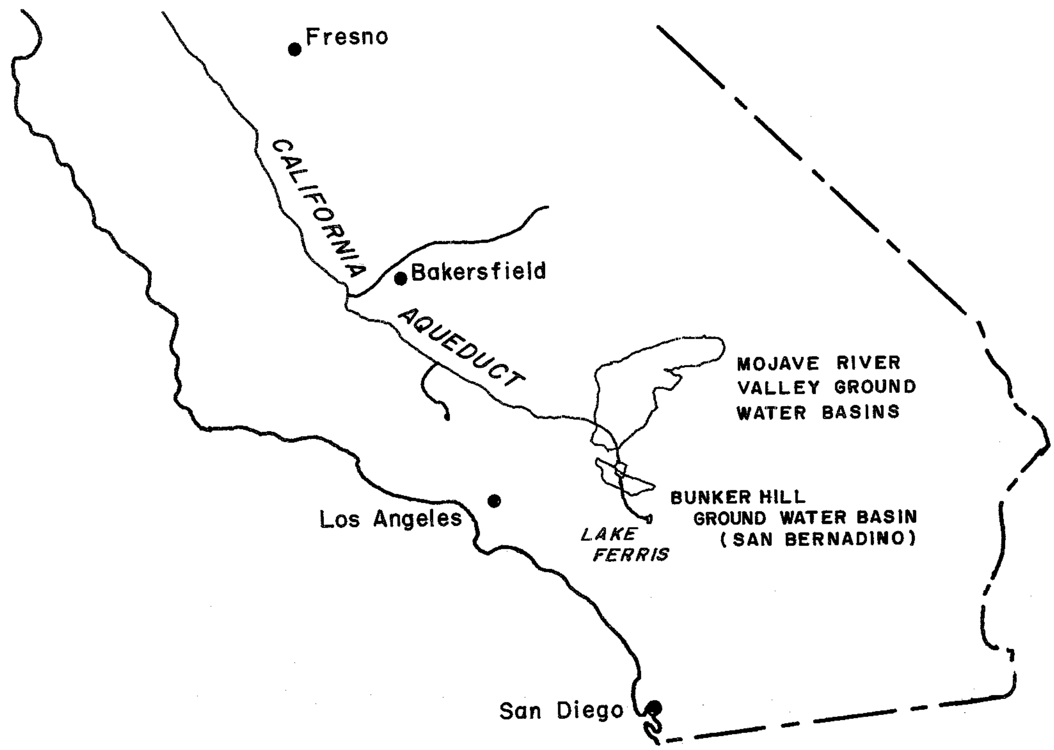

Figure 17. Kern River Intertie, California Aqueduct, and Demonstration Project Locations, (Marusak, 1980).

Blue Basin, Nebraska.

Recharge with floodwaters is being considered as a solution to severe groundwater overdraft problems in South Central Nebraska. Studies done at two reservoir sites in the Upper Blue River Basin suggest that seepage from flood-control reservoirs, encouraged by chisel plowing or cultivating reservoirs during dry periods, could significantly aid groundwater recharge (Eisenhauer, et al., Jan - Feb 1982). In addition to recharging the underlying portions of the Ogallala Aquifer, waters stored in flood-control reservoirs could relieve pressure on groundwater supplies by helping to provide irrigation water necessary to support Nebraska's agricultural economy.

Two projects incorporating both flood control and artificial recharge are currently being planned. The Big Sandy Creek Project in the Little Blue Natural Resources District will capture and allow infiltration of floodwaters in the Little Blue Basin. One reservoir has been completed and will be used to make further studies of recharge potential; four or five more reservoirs may be built. The proposed Big Blue Irrigation Project in the Upper Big Blue Natural Resources District (a part of the landmark water project), consists of six reservoirs which can be operated to impound flood flows during May through July storms (Upper Big Blue Natural Resources District, 1982). The primary source of water, however, will be Platte river waters diverted from Plum Creek (Figure 18). In addition to aiding in recharge, water supply, and flood control, the landmark water and Big Blue Irrigation Projects will also increase water-based recreation and benefit wildlife.

Artificial recharge is already being practiced in south-central Nebraska on a small-scale basis. Small pits have been adapted to farming operations to reuse irrigation water for recharge purposes. Recreation and flood control are secondary benefits.

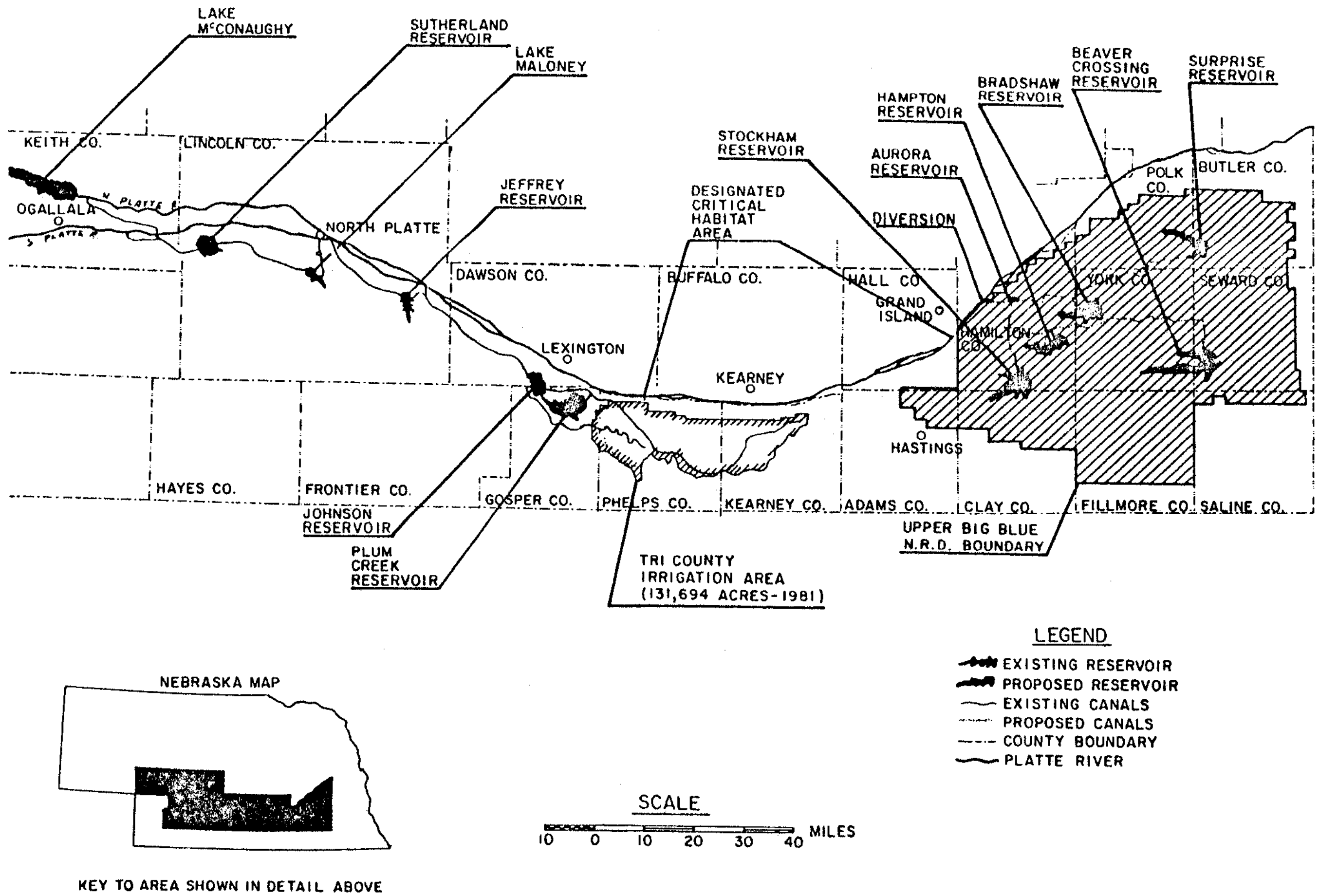

Figure 18. Big Blue Irrigation Project, (Upper Big Blue National Resources District, 1982).

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PLANNING CONJUNCTIVE USE SYSTEMS

Concept of Conjunctive Use

Three major components of every conjunctive use system are the surface water, the groundwater, and the transfer facilities. Figure 19 illustrates this concept. Surface water is commonly available through storage at new reservoirs, through stream withdrawals, through reallocation of storage and revised operating criteria at existing reservoir sites, and through wastewater. Groundwater is available through existing storage, through changing storage levels, and through revised withdrawal criteria. Both surface and groundwater can be managed in a similar fashion. Transfer facilities include those facilities which move water from surface water storage to groundwater storage or vice versa. This commonly includes conveyance, recharge, intermediate storage, and pumping facilities. In most cases, transfer will include a variety of such facilities, some existing, some new.

Operationally, surplus surface water is used to replenish the groundwater reservoir, and groundwater is pumped when there is a deficit of surface water. Amounts, timing, location, transfer facilities, and other system parameters and features will be site specific and depend upon the purposes of each system.

FIGURE 19

Concept of Conjunctive Use

SURFACE WATER ⟷	TRANSFER FACILITIES ⟷	GROUNDWATER
o New Reservoir Storage	o Conveyance	o Reservoir Storage
o Stream Withdrawal	o Recharge	o Storage Level
o Storage Reallocation and Revised Operating Criteria	o Intermediate Storage Change	o Withdrawal criteria
o Wastewater	o Pumping	

Basic Features of Conjunctive Use Planning

A prerequisite to most water supply planning and particularly to conjunctive use planning is the development of a water balance for the region, resources, and use being studied. Such a balance presents, systematically, information on the supply and use of water within a geographic region and for a specified period of time. Development of such a balance is described in a Guide Manual for Preparation of Water Balances (1980), published by the Hydrologic Engineering Center. With data available on supply and use, past, present, and future, and on the interconnections between supply and use, the stage is set to examine the desirability and feasibility of conjunctive use. Following the concept described previously the three principal tasks of conjunctive use planning are: (1) to determine the availability of the surface water resource for conjunctive use, (2) to determine the availability of groundwater and the storage capability of the groundwater reservoir, and (3) to determine what transfer facilities are necessary.

Surface Water Availability. Both high and low flows are of interest in planning for conjunctive use. High-flows are a source of surplus water which can be stored in a groundwater reservoir for supply at another time. Low-flows cause shortages in supply and require pumping from the groundwater reservoir. When analyzing surface water availability, this cyclic nature of streamflow should be considered. Availability must be coordinated with both demand and storage in terms of quantity, quality, time, and location. The principles and methods of planning are similar to those for water supply planning generally. The major difference is the need to consider a groundwater reservoir in the system both in terms of storage and supply.

The most useful analytical tool for determining surface water availability is a simulation model. Most simulation models in use today have the capability of including a variety of storage and diversion facilities in the simulation. This is ideal for conjunctive use planning. Using streamflow as input, a simulation model can simulate the operation of a network of rivers and reservoirs taking into account the quantity, time and location of flow volumes - both high and low. Results from the surface water simulation are used as input to a groundwater simulation model to complete the simulation of the operation of the conjunctive system. Specific simulation models are discussed in separate reports.

Low-flow frequency analysis and flow-duration analysis allow assignment of frequency and percent time values to streamflow rates and streamflow volumes for both flood and drought conditions. Such expressions of probability are indicators of risk and are commonly associated with the availability of natural streamflow. They are useful in conjunctive use planning in the same way they are in other types of water supply planning: to express the risk of drought or flood. Simulation and frequency/duration analysis are common tools for assessing surface water availability when streamflow is known. When streamflow records are not available, continuous simulation of the rainfall-runoff process may be necessary to model both drought and flood conditions. A variety of models are available. These models use precipitation, continuous over time, as input and produce, by modeling the runoff process, streamflow. With streamflow records generated, the other analysis techniques mentioned previously may be used to assess availability.

Groundwater Availability. The two principal tasks for assessing groundwater availability are to determine the nature and extent of the groundwater reservoir, and to determine the capability of the reservoir to store and produce water. The first task requires a study of the hydrogeology of the aquifer formation, its extent, inflow, outflow, water table elevation or piezometric head, and storage volume. Such an investigation will define the groundwater reservoir. The second task is to investigate the ability of water to flow to and from the reservoir. Parameters such as transmissivity, storage coefficient, hydraulic gradient, and infiltration rate should be defined. Once the nature and extent of the aquifer are known, its operation as part of the conjunctive use system can be simulated.

Computer models are available to simulate the operation of a groundwater reservoir given the physical parameters which define the aquifer and the pumping or recharge rate. Such a model serves to simulate the groundwater component given input from a surface water simulation. The groundwater model will provide information on the rate and volume of water which can be stored underground, the rate and volume which can be withdrawn, and the water or head elevations throughout the recharge, withdrawal cycle. When coupled with the surface water simulation, the two models can be an effective means of analyzing alternative arrangements for conjunctive use.

<u>Transfer Facilities.</u> Facilities, such as storage reservoirs or tanks, diversions, pumps, and infiltration ponds, can be included as components of the surface and groundwater simulation models. By including these in the models, various combinations of conjunctive use facilities can be evaluated. The linkage between the surface and groundwater models can be evaluated. The linkage between the surface and groundwater models can normally be handled by diversions from or inflows to the surface model and pumping from or recharge to the groundwater model. In studies where significant amounts of water infiltrate from surface streams or storage reservoirs to the groundwater aquifer, it may be necessary to formally link the surface and groundwater model. Most models do not have this formal linkage. Considering the time frame used in most conjunctive use studies and the aggregate values, it may be sufficient to simulate such infiltration as discrete diversions and recharges.

<u>Other Considerations in Planning.</u> As in most water resources planning, there are other considerations which must be addressed in planning for conjunctive use. Legal factors are of particular importance since both surface and groundwater rights may be involved: rights to the water and rights to store. Institutional and political alignments may have to be modified or developed and financing arrangements established. With respect to feasibility, not only must it be feasible from a hydrologic and engineering standpoint, but also economically, environmentally and socially. Because conjunctive use involves both surface and groundwater, these "other considerations" can be more complex and difficult than with a single resource. Detailed studies will often be required to identify options and plans for resolution of conflicts and problems.

Methods of Artificial Recharge

Methods of intentional artificial recharge are usually improvements upon forms of natural and incidental recharge. Recharge in a drainage channel, for example, can be increased by modifing flood control operations. While a wide variety of well-developed and well-defined artificial recharge techniques are currently in use, most major methods can still be classified as either surface infiltration or subsurface injection recharge.

Surface Infiltration. Surface infiltration methods involve retaining or slowly spreading water over an area and allowing gravity to cause water to percolate through non-saturated zones into groundwater aquifers. Unconfined aquifers lying under highly permeable soils are suitable for recharge by surface infiltration methods.

Facilities used for surface infiltration include spreading basins or ponds, natural and man-made channels, furrows and ditches, floodplains, and irrigation systems. Recharge by use of spreading basins, shallow flat-bottomed excavations of variable surface dimensions is often the most economical method of artificial recharge, requiring low construction and operation costs. Construction of series or groups of basins permits maximum use of sources of water, while providing potential solutions for clogging problems which afflict almost all recharge schemes (Figure 20). Several basins can serve as desilting structures allowing sediment, which reduces infiltration rates, to settle out. Concentrations of sediment in waters used for basin recharge should be less than 1,000 mg/1 (United Nations, 1975). Battery spreading, which involves allowing a few basins to dry while using the rest for recharge, also maintains infiltration rates, as drying discourages microbial growth which can clog soil pores and reduce permeability. Other means of limiting clogging effects in basins include adding flocculents or chlorine to recharge waters, passing waters through various types of filters, or occasionally dredging out basins to remove silts and clays.

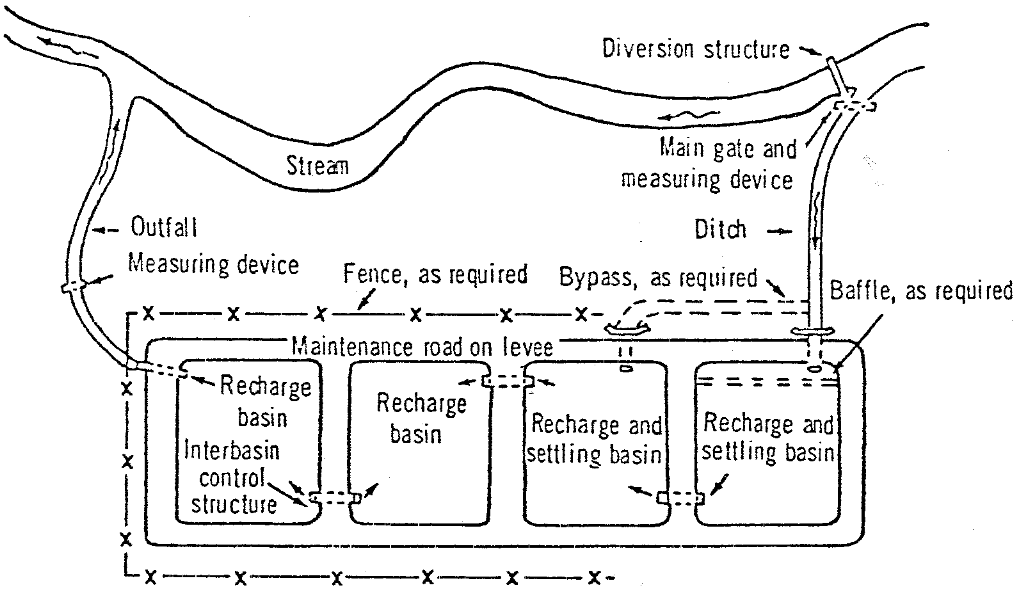

Figure 20. Typical Plan of Basin-Type Recharge Project, (Pettyjohn, 1981).

Clogging is usually a lesser problem in recharge systems with moving waters, such as closely spaced networks of furrows or ditches, as sediment is carried through the system and rejected (United Nations, 1975). Waters flowing through natural or man-made channels (or in any body of water) can be drawn into aquifers by pumping nearby wells to create a hydraulic gradient, a method known as induced infiltration (Figure 21). Deposit of sediments, however, does inhibit recharge in channels when dikes, levees, weirs, and small dams are used to slow flows and encourage percolation.

Surface infiltration methods are often impractical, when land availability is limited, because practices such as flooding plains for recharge or spreading water in basins occupy large amounts of land. Passing water through irrigation systems for infiltration purposes, on the other hand, exploits land rarely used during non-irrigating seasons (Espina, 1980).

Subsurface Injection. - Pits, shafts and wells are the main structures used for subsurface injection recharge. These permit passage of water into aquifers underlying solids of low permeability or impervious zones (Pettyjohn, 1981).

Disposal ponds, abandoned gravel pits, and abandoned mining areas can all be used for pit recharge, providing access to more permeable soils directly overlying aquifers (Figure 22). Pits are relatively inexpensive to excavate and easy to operate. Shafts are passages, small in diameter and short in length, which link sources of water to zones of permeability when thin impervious layers prevent infiltration. Shafts can be placed in lined channels to allow streamflows to recharge groundwater.

Injection wells provide a means of recharging confined aquifers lying at great depths below the land surface. Use of injection wells involves extremely high construction, operation, and maintenance costs, as injection wells are in many ways similar to extraction wells (Figure 23). Recharge through wells allows for little or no percolation of water passing from the surface to a confined aquifer, a process which substantially improves water quality in surface infiltration methods. To insure that groundwater is not contaminated and that a build up of sediment deposits or bacteria does not clog wells, only extremely high quality water should be used for this recharge method.

In addition to recharging confined aquifers, subsurface injection methods are often employed to recharge unconfined aquifers in urban areas, where spreading basins and other large facilities are economically impractical. Subsurface injection is also used in mountainous areas, where surface infiltration methods are rendered ineffective by large gradients, and it is used in coastal areas to form freshwater lenses which inhibit seawater intrusion.

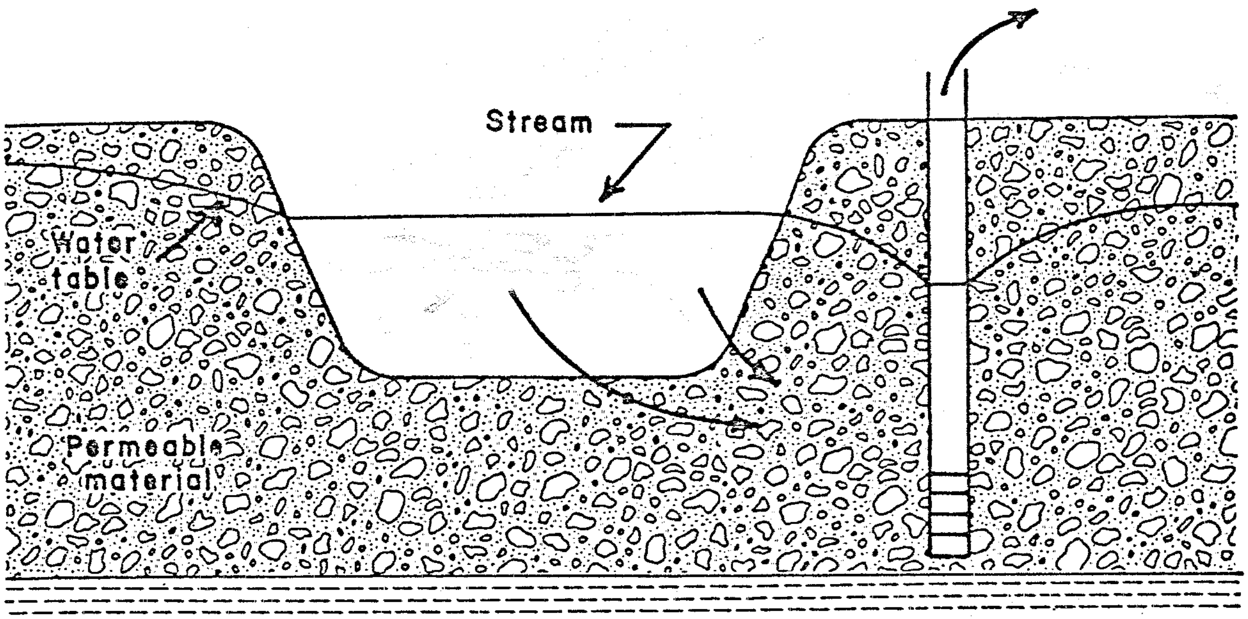

Figure 21. Induced Infiltration , (Pettyjohn, 1981).

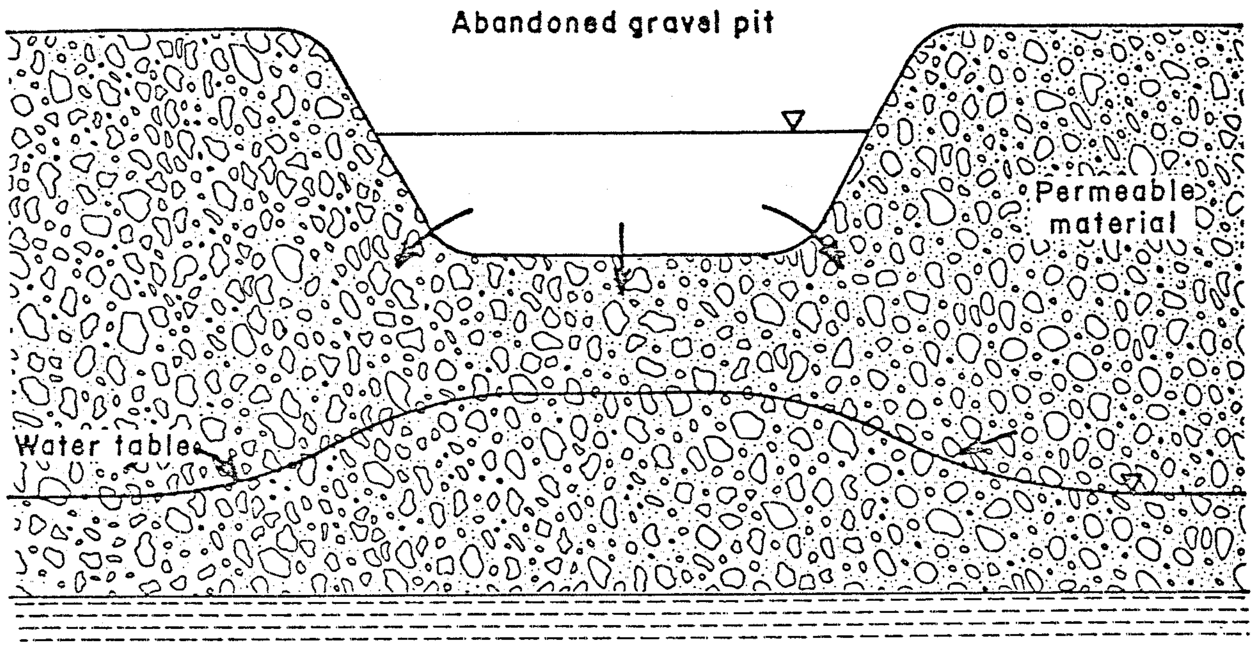

Figure 22. Abandoned Gravel Pit, (Pettyjohn, 1981).

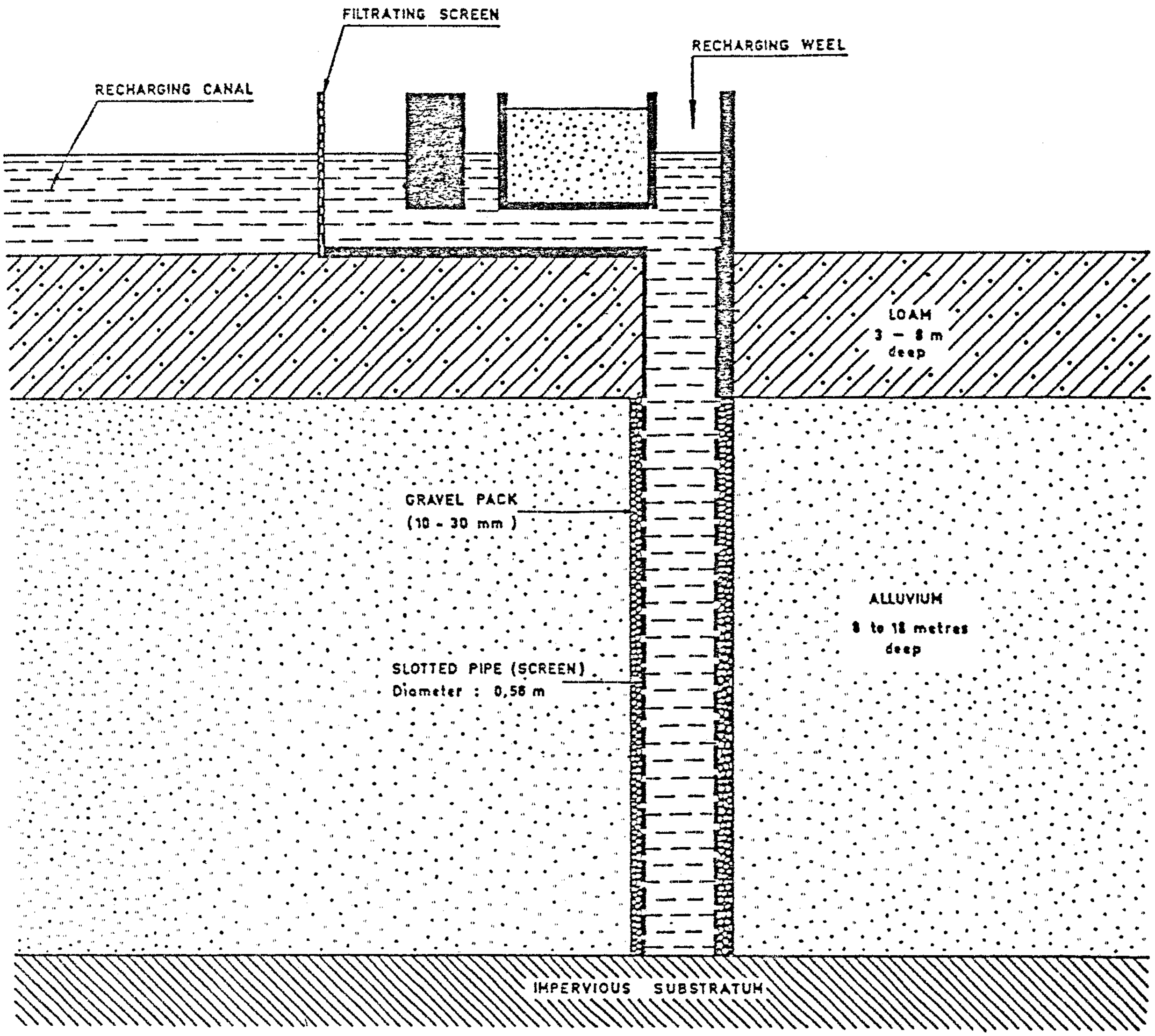

Figure 23. Injection Well, (United Nations, 1975).

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