TEXAS DEPARTMENT OF WATER RESOURCES

REPORT 220

ARTIFICIAL GROUND-WATER RECHARGE AS A WATER-MANAGEMENT TECHNIQUE ON THE SOUTHERN HIGH PLAINS OF TEXAS AND NEW MEXICO

By

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FOREWORD

Effective September 1, 1977, Texas three water resources agencies, the Texas Water Rights Commission, the Texas Water Development Board, and the Texas Water Quality Board, were consolidated to form the Texas Department of Water Resources. A number of publications prepared under the auspices of the predecessor agencies are being published by the TDWR. To effect as little delay as possible in production of these publications, references to these predecessor agencies will not be altered except on their covers and title pages.

Harvey Davis
Executive Director

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ARTIFICIAL GROUND-WATER RECHARGE AS A WATER-MANAGEMENT TECHNIQUE ON THE SOUTHERN HIGH PLAINS OF TEXAS AND NEW MEXICO

ABSTRACT

Artificial ground-water recharge of the Ogallala Formation of late Tertiary age is a water-management technique that may be of significant value on the Southern High Plains of Texas and New Mexico. Under specific conditions artificial recharge by use of either water-spreading basins or injection wells is a proved method of storing water that is available from the playa lakes on the Southern High Plains of Texas and New Mexico. Experience gained through field tests and laboratory research indicates that spreading basins are the most economical method of recharge in most areas of the Southern High Plains; however, in many areas where the surficial materials have low vertical permeability, and where the spreading-basin method cannot be used successfully, water can be recharged through injection wells.

Artificial recharge of playa-lake water is more likely to be successful if the water is collected from near the surface of the playa lakes, treated and clarified in a settling basin, and recharged through a system that minimizes the clogging effect of suspended sediment. Reduction of the infiltration rate is minimized if the recharged water contains little or no suspended sediment.

Case histories of recent recharge experiments on the Southern High Plains, the results of laboratory studies of sediment flocculation of playa-lake water, and a cost analysis of recharge systems are presented in this report.

ARTIFICIAL GROUND-WATER RECHARGE AS A WATER-MANAGEMENT TECHNIQUE ON THE SOUTHERN HIGH PLAINS OF TEXAS AND NEW MEXICO

INTRODUCTION

The Southern High Plains of Texas and New Mexico (Figure 1) is one of the most productive agricultural areas in the United States. The high productivity results largely from irrigation by use of water pumped from the sand and gravel of the Ogallala Formation. This aquifer extends from New Mexico and West Texas to South Dakota and occupies an area comparable in size to the State of California. The Ogallala originally extended as an unbroken alluvial plain from the mountains in New Mexico to Central Texas, but uplift of the alluvial plain and erosion by the Pecos and Canadian Rivers have hydrologically isolated the formation underlying the Southern High Plains.

Under recent climatic conditions, less than 0.08 inch (2 mm) of water per year is added to storage in the Ogallala Formation by infiltration from rainfall (Theis, 1937; Brown and Signor, 1973). Meanwhile, an average of about 12 inches (305 mm) of water is being pumped from storage each year, thereby decreasing the quantity of water remaining for use in irrigation (Figure 2). The decrease is particularly critical in the southern part of the area, where the saturated thickness of the Ogallala aquifer is the least. At the present (1976) rate of water use, most of the irrigated farms in the south and central parts of the Southern High Plains will become dryland farms before the year 2000 (Hughes and Harman, 1969). Substantial declines in the volume of agricultural production and farm income have been projected (Hughes and Harman, 1969) to accompany the decline in irrigated acreage (Figure 3).

Precipitation, which provides the only renewable water supply on the Southern High Plains, decreases from east to west (Figure 4) and ranges from about 20 inches to about 12 inches (508 to 305 mm). In the central part of the area, the average annual precipitation is 18 inches (457 mm), but precipitation has ranged from less than 9 inches to nearly 40 inches (229 to 1,016 mm) (Figure 5). During the 1950's, average annual precipitation recorded at Lubbock was less than 15 inches (381 mm) during 4 years, and exceeded 18 inches (457 mm) in only 1 year (Orton, 1966). In an average year, the greatest amount of precipitation occurs during the spring and early fall. Precipitation during July and August is below that needed by most crops. Irrigation is

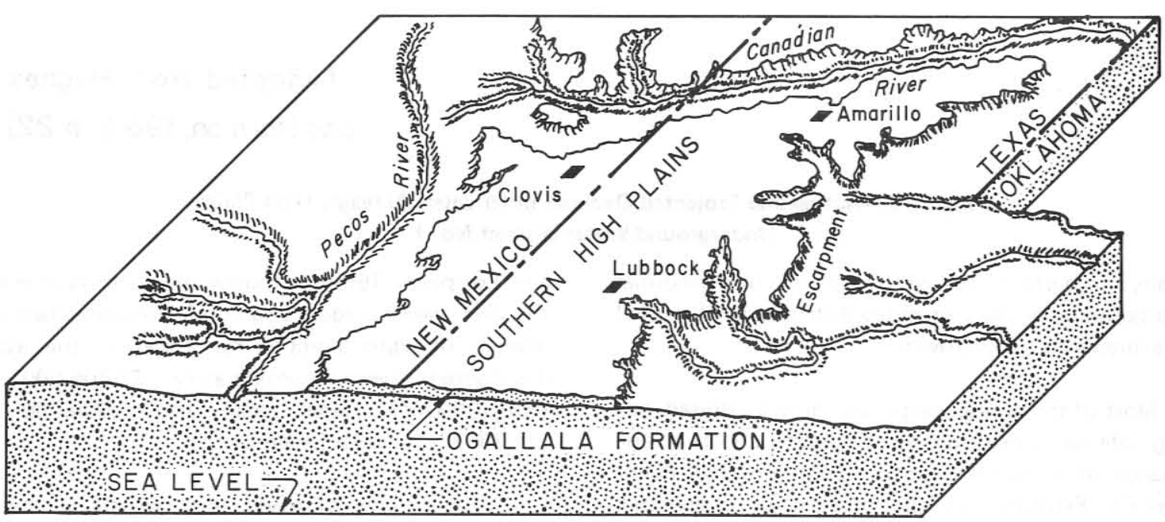
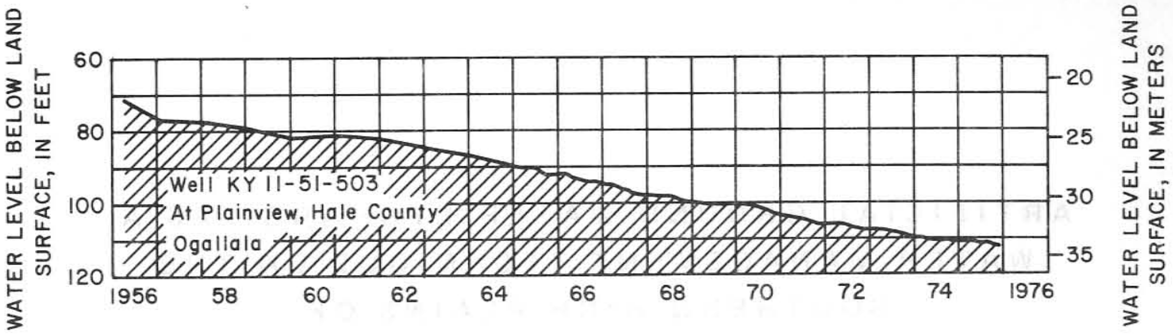
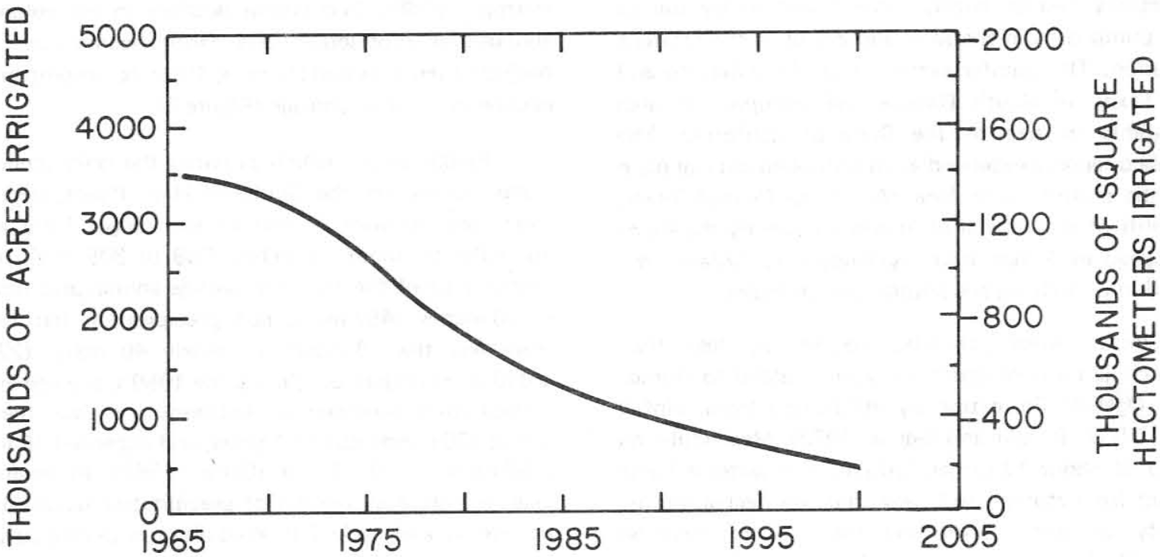


Figure 1.—Physiography of the Southern High Plains of Texas and New Mexico



Texas Water Development Board, 1975 p.23

Figure 2.—Historical Decline of the Water Level in the Ogallala Formation at Plainview, Hale County, Texas



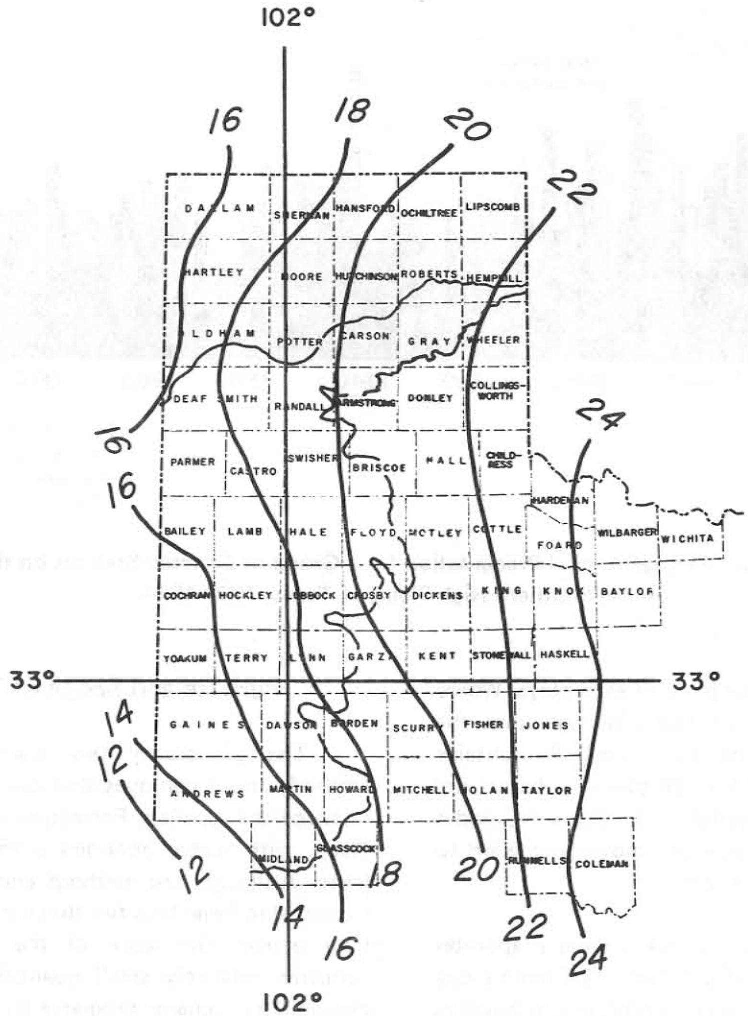
(Adapted from Hughes and Harman, 1969, p. 22)

Figure 3.—Actual and Projected Declines in Irrigated Acreage, High Plains Underground Water District No. 1

critically important during years of below-normal precipitation or in years when the distribution of rainfall is unfavorable for crop growth.

Most of the rainfall evaporates or is transpired, but during intense rainstorms, some runoff collects in the thousands of playa lakes on the Southern High Plains (Figure 6). Estimates of the amount of water that collects in these lakes range from 1.8 to 5.7 million acre-feet (2.2×10^9 to 7.0×10^9 m^3) per year (Hauser and Lotspeich, 1968). Although the quantity of water in the playa lakes is equal to a significant percentage of the amount of water pumped for irrigation, the water is distributed over approximately 22,000,000 acres (89,000 km^2) rather than the 6,000,000 acres (24,280 km^2) under irrigation.

The volume of water that collects in the playa lakes is dependent on the frequency and intensity of precipitation during the spring and fall and on the



EXPLANATION

22 —— ANNUAL RAINFALL, IN INCHES
INTERVAL 2 INCHES

BOUNDARY OF THE SOUTHERN HIGH PLAINS

0 50 100 MILES

0 50 100 150 KILOMETERS

Base from U.S. Geological Survey map of Texas, 1:1,000,000 (After Orton, 1966)

Figure 4

Areal Distribution of Rainfall on the Southern High Plains of Texas

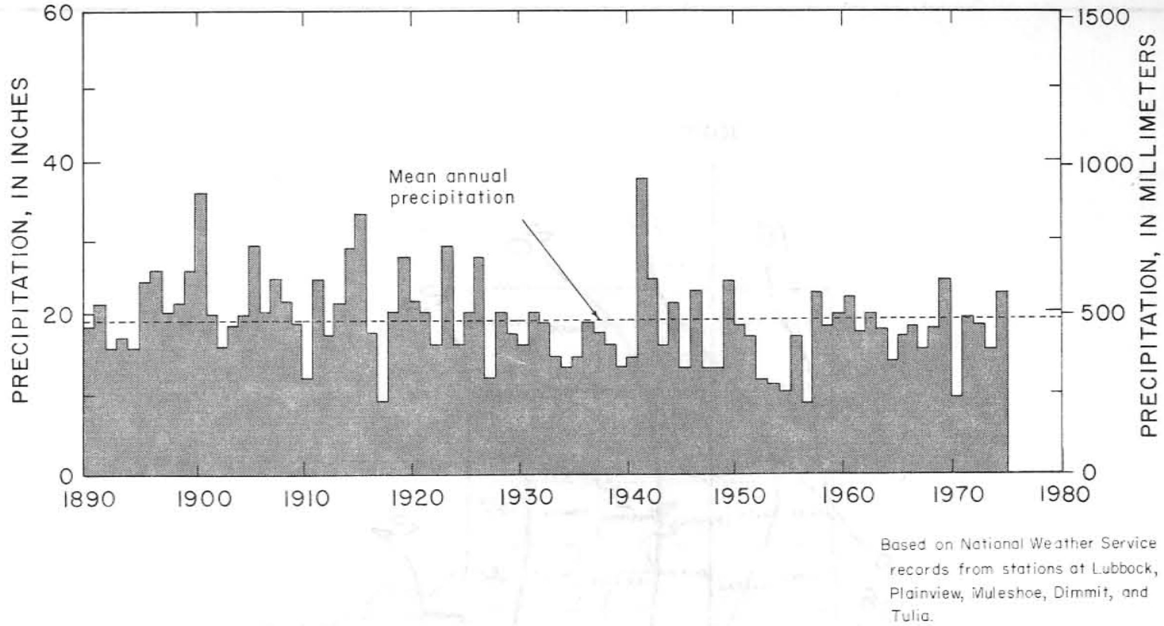


Figure 5.—Average Annual Precipitation for a Group of Selected Stations on the on the Southern High Plains of Texas, 1890-1974

characteristics of the drainage basin of each playa. Where the drainage basin is largely covered with vegetation, the runoff rate is slower, but the water generally contains less suspended sediment. Most of the lake basins are sealed with clay in the central part; therefore, under natural conditions, little water can move downward to recharge the ground-water system.

The water impounded in playa lakes evaporates rapidly (Figure 7). Losses of 0.5 inch (12.7 mm) a day are common during the summer months, and as much as 25 acre-feet (3.1×10^4 m^3) may evaporate in 12 days from a 50-acre (20-hm^2) playa. The aquifer is a suitable reservoir for storing this water if it can be emplaced and withdrawn at a cost that is acceptable for its anticipated use. Rayner (1967) estimated that there is enough subsurface space within a 21-county area on the Southern High Plains of Texas to store nearly three times as much water as can be stored in all of the major surface reservoirs in Texas.

Purpose and Scope of This Report

The purpose of this report is to describe the methods and techniques that can be used to artificially recharge the Ogallala Formation of the Southern High Plains with water obtained primarily from the playa lakes. Although the methods and techniques could be extended to large facilities that would be operated over a long period, the scope of the discussions presented concerns relatively small quantities of water that are available for recharge programs on individual farms.

Metric Conversions

For readers interested in using the metric system, metric equivalents of English units of measurements are given in parentheses. The English units used in this report may be converted to metric units by the following conversion factors.

From			To obtain	
Unit	Abbreviation	Multiply by	Unit	Abbreviation
acres	—	0.4047 .004047	square hectometers square kilometers	hm^2 km^2
acre-feet	—	1233	cubic meters	m^3
feet	—	.3048	meters	m
feet per day	ft/d	.3048	meters per day	m/d

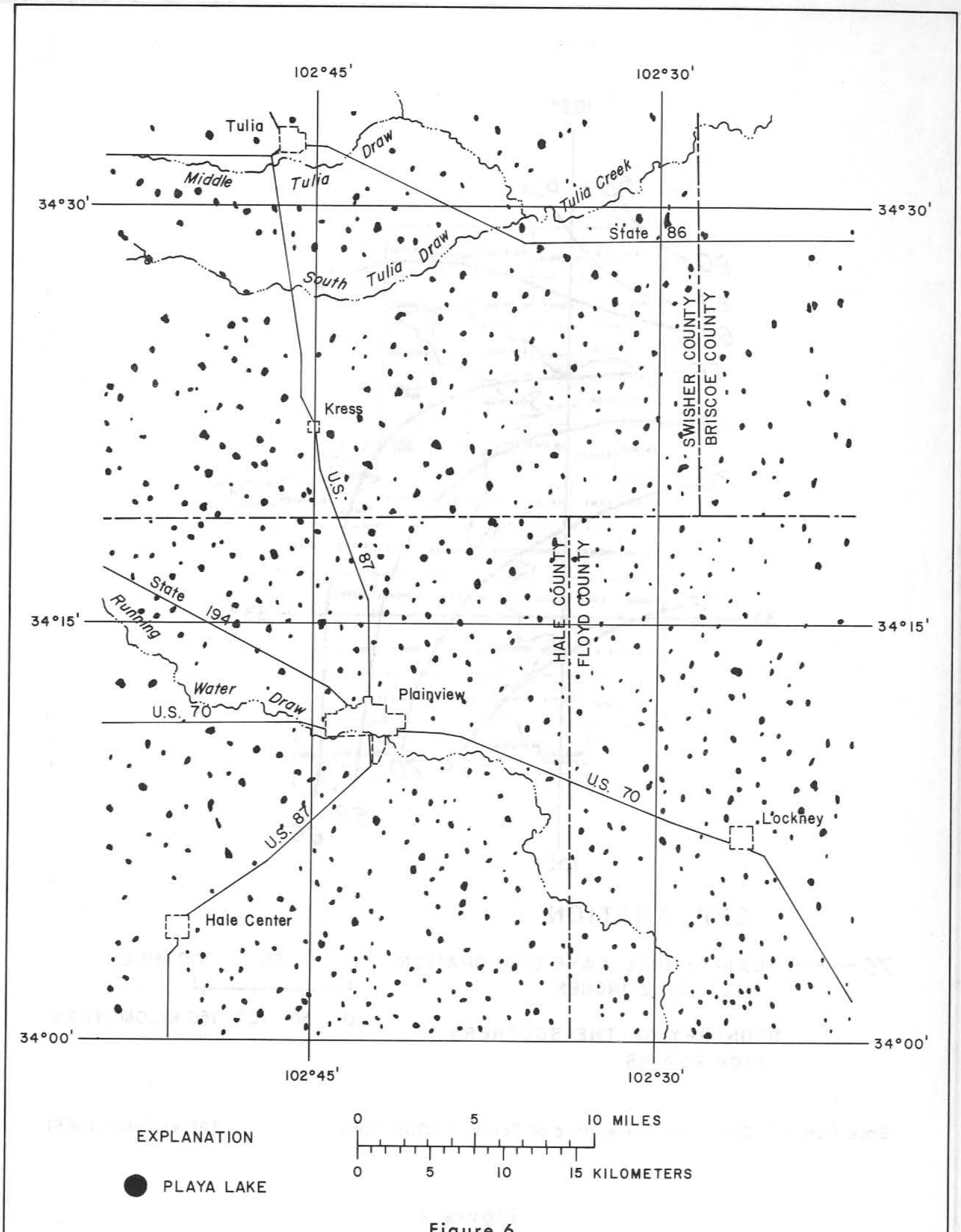
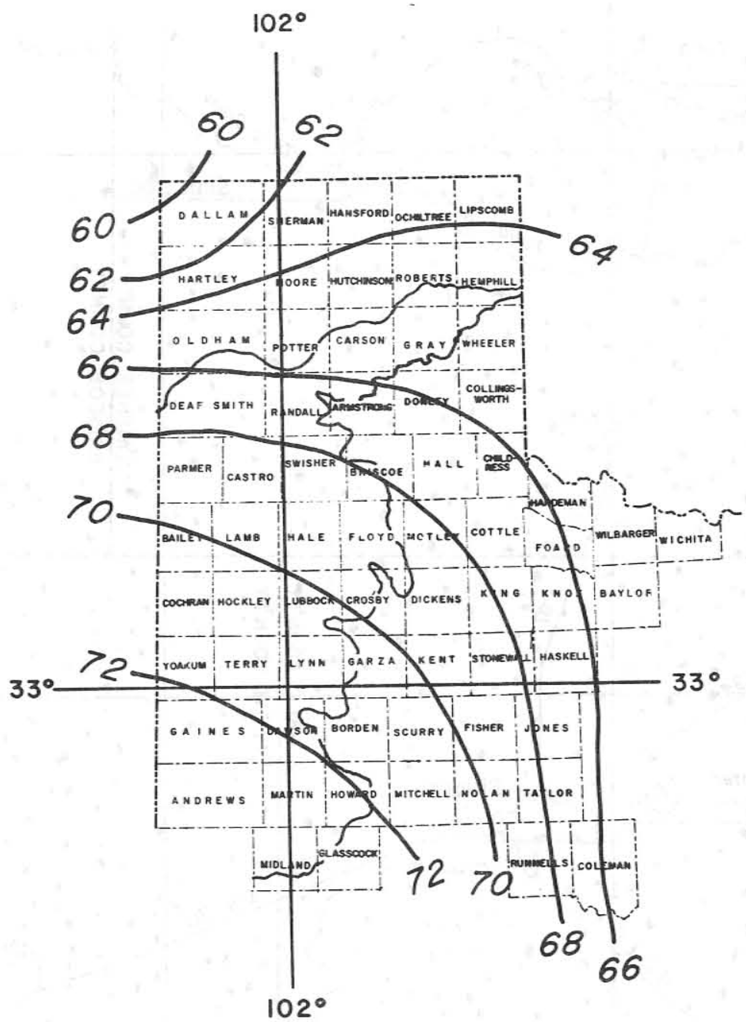


Figure 6
Areal Distribution of Playa Lakes Near Plainview, Texas

Base from U.S. Geological Survey 1:250,000



EXPLANATION

70 —— MEAN ANNUAL LAKE EVAPORATION, INTERVAL 2 INCHES

BOUNDARY OF THE SOUTHERN HIGH PLAINS

0 50 100 MILES

0 50 100 150 KILOMETERS

Base from U.S. Geological Survey map of Texas, 1:1,000,000, (After Orton, 1966)

Figure 7

Mean Annual Lake Evaporation on the Southern High Plains of Texas, 1946-1955

From			To obtain	
Unit	Abbreviation	Multiply by	Unit	Abbreviation
feet per mile	ft/mi	.189	meters per kilometer	m/km
feet per year	ft/yr	.3048	meters per year	m/yr
gallons per minute	gal/min	.06309	liters per second	l/s
gallons per minute per foot	gal/min/ft	.207	liters per second per meter	l/s/m
inches	—	25.4	millimeters	mm
pounds per square inch	lb/in^2	.07031	kilograms per square centimeter	kg/cm^2
square feet	ft^2	.0929	square meters	m^2

METHODS OF ARTIFICIAL RECHARGE

Two basic methods of artificial recharge are: (1) Use of water-spreading basins from which water infiltrates to the water table; and (2) use of injection wells to pump water into the aquifer. Both methods have been used successfully on the Southern High Plains, but both methods are subject to limitations or failure.

Recharge Through Spreading Basins

Recharge by use of spreading basins is suitable for many areas of the Southern High Plains and is probably the most economical method of artificial recharge. This method is most effective where moderate to high rates of infiltration can be maintained. The initial recharge rate should be at least 0.5 to 1 vertical foot (0.15 to 0.3 m) per day; when the initial rate is lower, the long period required for recharge will result in excessive evaporation of the available water.

High infiltration rates can be obtained by: (1) Selection of an area that is underlain by highly permeable sediments; (2) removal of suspended sediment in the recharge water; (3) alternate use of several spreading basins to permit drying and rejuvenation of the basins between recharge operations; (4) maintenance of the highest possible water level in the basin; (5) continuous ponding of water in the basin; (6) removal of organic material from the water and from the soil zone; and (7) prevention of the growth of aquatic plants and algae in the basin.

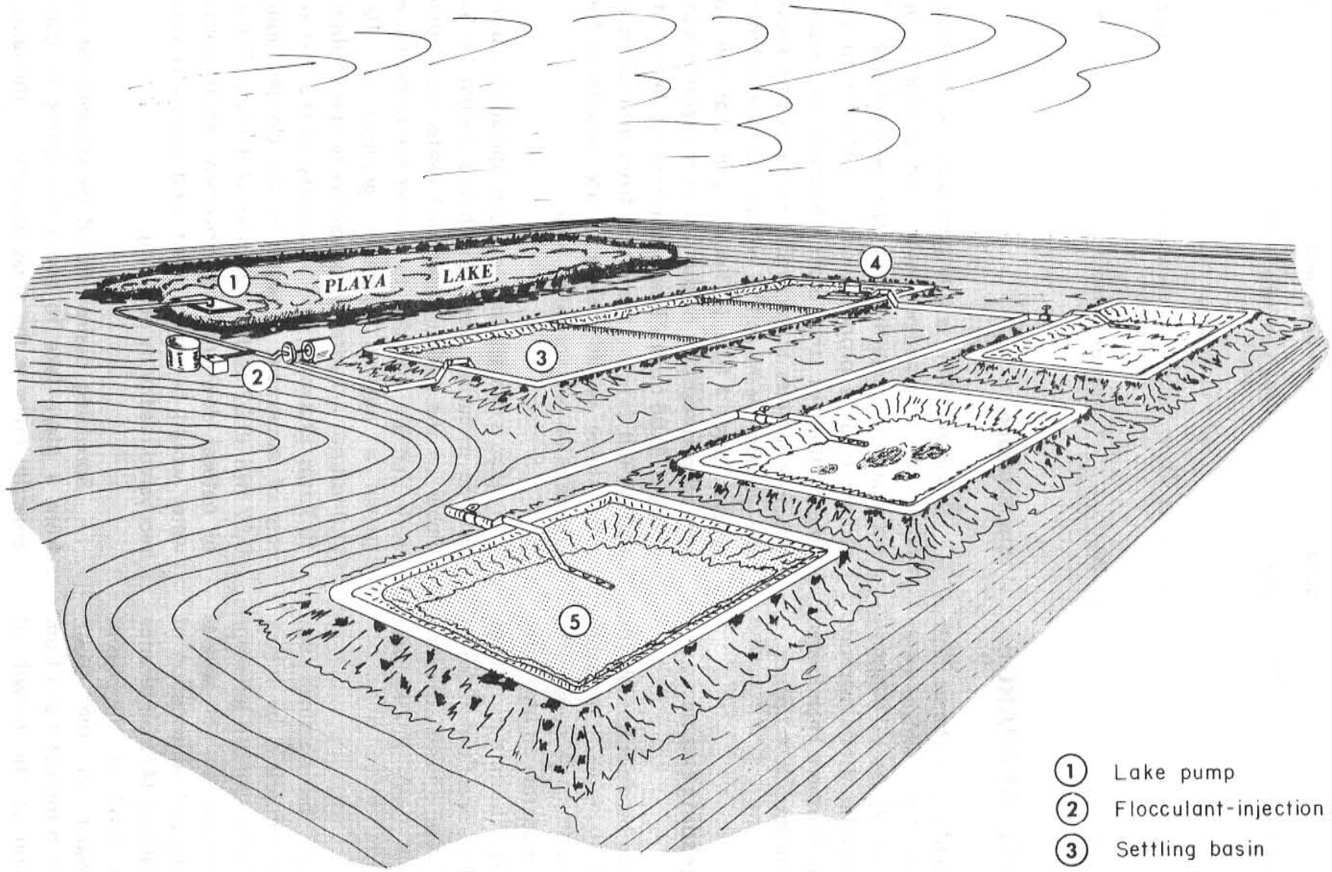
Figure 8 shows an idealized spreading-basin installation. Water is (1) pumped from a playa lake, (2) treated with a chemical flocculant to speed up settling of the suspended material, (3) held in a settling basin to allow sedimentation, and (4) pumped into one of three spreading basins.

Site Selection

Site selection is a critical factor in the success or failure of a spreading basin. Test drilling is usually necessary to determine if the permeability of the sediments at a proposed site is sufficient to warrant construction of the basin. Analysis of data from test-hole samples at successful recharge sites show that the vertical permeability of the surface sediments is greater than 1 ft/d (0.3 m/d), and that the average vertical permeability of the rest of the section is at least 0.2 ft/d (0.06 m/d). The occurrence of layers of clay that would prevent the water from infiltrating to the water table would render a site unsuitable for the construction of a spreading basin.

If it is not feasible to locate spreading basins near existing irrigation wells, the basins should be located higher on the hydraulic gradient (water table) than the wells that are intended to recover the recharged water. Under a natural hydraulic gradient of 10 ft/mi (1.9 m/km), a hydraulic conductivity (permeability) of 10.7 ft/d (3.3 m/d), and a porosity of 0.3, the average rate of movement of water in the Ogallala aquifer is 0.07 ft/d (0.02 m/d) or 25 ft/yr (7.6 m/yr). The extent of natural downgradient movement of the recharged water would be insignificant, and the water could be recovered readily by pumping.

Spreading basins should be situated far enough from a playa lake to avoid the layers of clay that generally underlie the areas adjacent to the lakes. If a basin is constructed adjacent to a playa lake by removing the clay to expose more permeable materials, the excavation tends to be refilled rapidly with clay by runoff from subsequent precipitation. During periods of unusually heavy rainfall, such as occurred in 1941, water may fill playas to depths of tens of feet (several meters); and spreading basins located above the potential high-water levels will be available for recharge when



(1) Lake pump
(2) Flocculant-injection system
(3) Settling basin
(4) Clear-water pickup
(5) Spreading basins

Figure 8

Idealized Spreading-Basin Installation With Water-Intake Systems (Lake Pump and Clear-Water Pickup), Flocculant-Injection System, and Settling Basins

these large quantities of water are obtainable. If possible, the basins should be situated near an irrigation well because the infiltrating water would move toward the cone of depression formed by the well and would remain in the immediate vicinity of the well.

The hydraulic conductivity of the sediments below the soil zone can be estimated from analyses of well cuttings, core samples, and geophysical logs. Data collected at several test-hole sites on the Southern High Plains show that the vertical hydraulic conductivity of the Ogallala Formation ranges from less than 0.006 ft/d (0.0018 m/d) to more than 100 ft/d (30 m/d). In many areas where the carbonate content of the clay zones is high, the carbonates have been selectively leached; and the leached zones have secondary hydraulic conductivity that is greater than the hydraulic conductivity of the very permeable sand sections of the Ogallala Formation.

The occurrence of a perched water table that persists for long periods of time is indicative of the occurrence of layers of low hydraulic conductivity above the regional water table. Because these layers restrict the vertical movement of water, the occurrence of a perched water table indicates that the site is not suitable for construction of a spreading basin.

A technique for measuring vertical hydraulic conductivity in the unsaturated zone by measuring changes in atmospheric pressure at the land surface and at depth has been described by E. P. Weeks (written commun., 1976). This method requires one test hole that penetrates the zone between the surface and the water table. Although subject to error, this method is the most accurate procedure developed to date.

Water-Intake Systems

The concentration of suspended sediment in water obtained from playa lakes should be reduced as much as possible to prevent clogging of the bottom of a spreading basin. One of the most effective means of decreasing the sediment load is to withdraw the water from the surface of the playa lake by use of a floating intake system. Figure 9 illustrates the types of floating-water intake systems that have been used successfully on the Southern High Plains. Whatever system is used, the intake port should be placed within a fine-mesh wire enclosure that will keep floating debris and small aquatic animals from entering the intake pipe. An enclosure that provides a flow-through area large enough for the water velocity through the screen to be about 0.5 foot (0.15 m) per minute would allow swimming creatures to move away from the intake without becoming caught in the screen. A 10-foot (3-m) square enclosure in 3 feet (0.9 m) of water passing 500 gal/min (32 l/s) through the enclosure would fulfill the requirement.

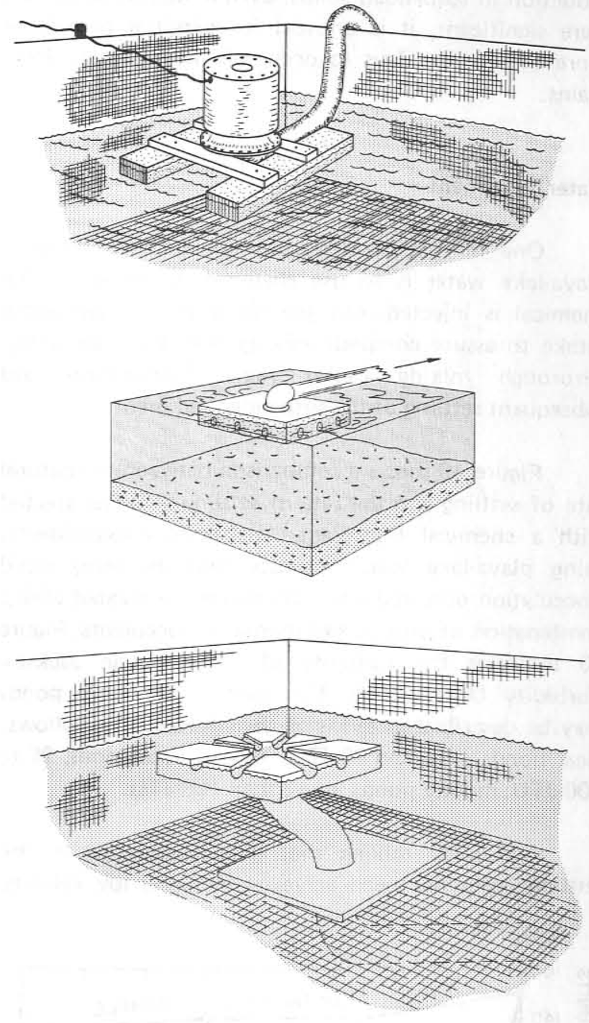


Figure 9.—Types of Floating Water-Intake Systems

Wind has an effect on the amount of suspended sediment in playa-lake water. High winds create turbulence in the shallow playa lakes, and turbulent water lifts sediment from the bottom of the playa and keeps it in suspension in the water. The higher the wind velocity and the shallower the water, the greater the sediment load at a given time. Whenever possible, recharge operations should be conducted during periods of little or no wind. Frequently, wind velocities are relatively low during the nights and early mornings, even in the spring when daytime wind velocities are usually high.

Windless periods of 1 to 4 hours, which permit the settling of sediments, frequently result in a 50 percent or greater reduction in the amount of suspended sediment. Longer windless periods usually result in little additional reduction in suspended solids. Even if additional settling were significant, it is unusual for windless periods or more than a few days to occur on the Southern High Plains.

Water Treatment

One method of reducing the sediment load in playa-lake water is to use chemical flocculation. The chemical is injected into the water at the lake-pump intake to assure complete mixing with the lake water. Thorough mixing causes rapid flocculation and subsequent settling of the suspended sediment.

Figure 10 shows a comparison between the natural rate of settling and the rate of settling in water treated with a chemical flocculant.[1] Laboratory experiments using playa-lake water indicate that the most rapid flocculation occurred when the water was treated with a combination of organic and inorganic flocculants. Figure 10 indicates the turbidity of the water in Jackson Turbidity Units (JTU). For comparison, farm ponds may be described in terms of their turbidity as follows: clear ponds, less than 25 JTU; intermediate ponds, 25 to 100 JTU; muddy ponds, more than 100 JTU.

Additional mixing that aids flocculation in the settling basin has been achieved by using low-velocity directional-outlet jets where the water enters the basin (Figure 11). Settling of the flocculated particles then occurs in a settling basin as the water gradually moves from the inlet to the outlet. Several screen-wire baffles placed at intervals across the basin will assist in retaining the flocculated sediment and will prevent remixing of the floc with the recharge water. A settling basin about 100 feet long, 10 feet wide, and 10 feet deep (30 X 3 X 3 m) would be about 30 percent filled by sediment after recharge of about 100 acre-feet (123,300 m^3) of playa-lake water that contains approximately 100 mg/l (milligrams per liter) of suspended sediment. To maintain adequate retention time, the accumulation of sediment should be removed from the settling basin when 30 percent of the basin capacity is filled with sediment.

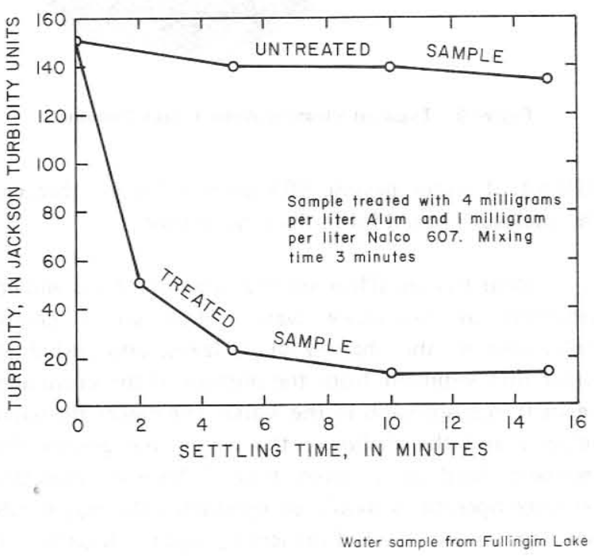


Figure 10.—Comparison of the Natural Rate of Settling of Suspended Sediment and the Rate of Settling in Water Treated With a Chemical Flocculant

[1] The use of brand names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey or the Texas Department of Water Resources.

A shallow area at the exit end of the settling basin, or a floating intake pipe, helps assure that the recharge water is obtained from near the settling-basin surface and therefore contains a low concentration of suspended sediment. The long axis of the settling basin should be perpendicular to the prevailing-wind direction to minimize agitation of the newly formed floc by wave action.

Construction and Operation of Spreading Basins

Spreading basins should be excavated to a depth that is sufficient to place the bottom of the basin in permeable material. In areas where the surface material is as permeable as the deposits at greater depth, a basin can be constructed by building a retention berm embankment without excavation. Berms constructed about 3 feet (1 m) above the floor of the basin, with a slope no greater than 2:1 work well to minimize the washing of fine sediment from the berm to the basin.

Experiments by the Agricultural Research Service at Bushland, Texas, (Aronovici, Schneider, and Jones, 1972) show that ridge-and-furrow plowing within a spreading basin helps to maintain high permeability for longer periods of recharge. Sediment in the recharge water washes off the ridges and accumulates in the furrows, thereby maintaining high permeability on the ridges. In addition, ridge-and-furrow plowing greatly increases the surface area of the basin.

Initial recharge rates tend to be low because air must be dissolved from the unsaturated zone as the recharge water moves from the bottom of the basin to the water table. To maintain maximum rates, the spreading basin should be kept filled with water at all times to prevent air from being reintroduced, and the water should be kept at the highest possible level in the recharge basin.

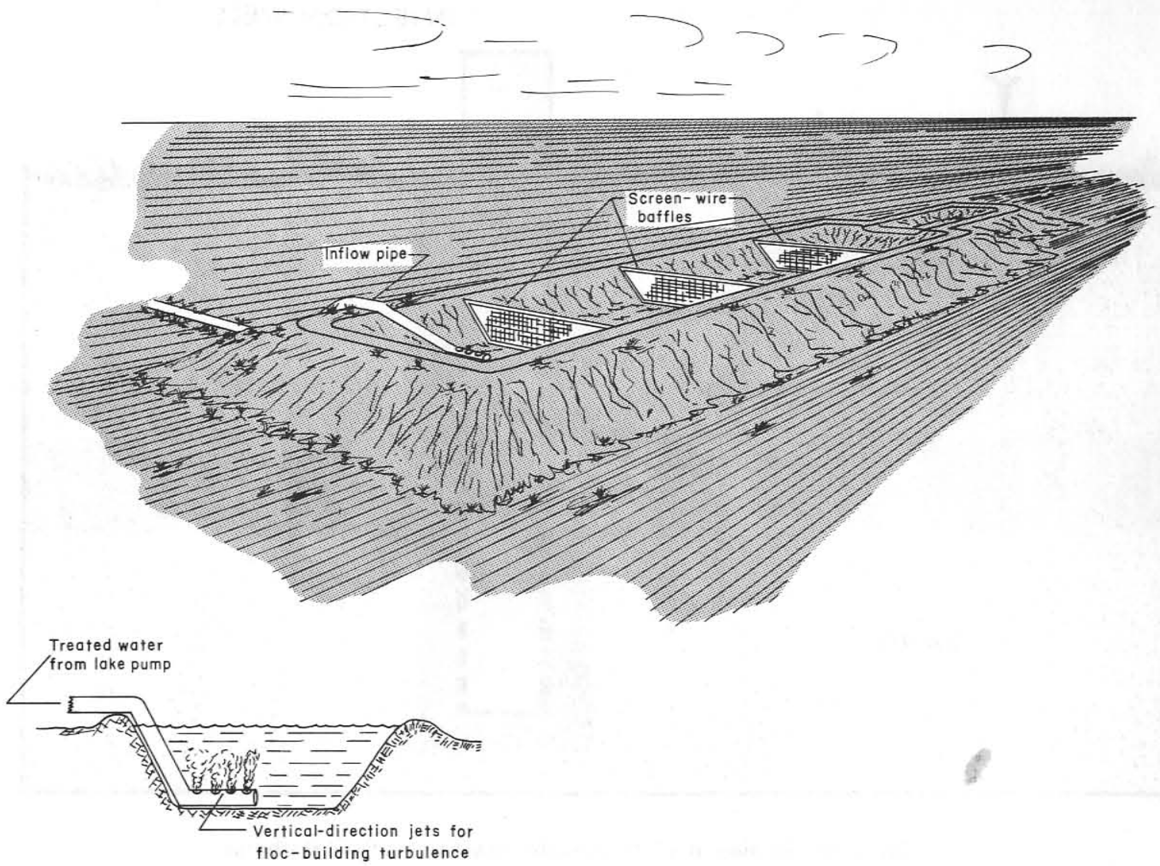


Figure 11.—Placement of Screen-Wire Baffles and Inflow Pipe in a Settling Basin

Peak recharge rates of more than 1 vertical ft/d (0.3 m/d) can be expected in most areas on the Southern High Plains. This rate will gradually decrease as sediment covers the bottom of the basin or as the growth of anaerobic bacteria reduces permeability (Wood and Bassett, 1975). Locally, solution channels and animal burrows in the bottom of the basin may permit recharge to continue for long periods of time without a significant decrease in the rate of infiltration.

If the rate of recharge declines significantly because of sediment clogging or bacterial growth, recharge from the basin can be stopped and the operation transferred to another basin. Permeability can be restored in the clogged basin by allowing it to dry thoroughly and by scraping the bottom to remove the deposits of fine sediment. Plowing after drying and scraping speeds up the rejuvenation process when the clogging is due to the growth of anaerobic bacteria. Drying can be continued in one basin until clogging occurs in another basin, at which time the dried and rejuvenated basin can be put into operation again.

Recharge Through Injection Wells

Injection wells provide a means of placing water directly into an aquifer at a location and depth from which it can be recovered. Construction and maintenance costs for injection wells are usually much higher than the costs for spreading basins, and the useful life of an injection well may be less than that of a spreading basin. At many sites, however, the advantages of using an injection well may make it the preferred method of artificial recharge. Where layers of low permeability occur between the land surface and the water table, recharge through injection wells may be the only feasible method available.

Figure 12 shows a section in which conditions are suitable only for recharge through injection wells. An extensive layer of clay of low permeability occurs between the land surface and the water table; therefore, recharge through a spreading basin would result in a shallow body of perched water that could not be recovered easily. Below the clay layer injected water

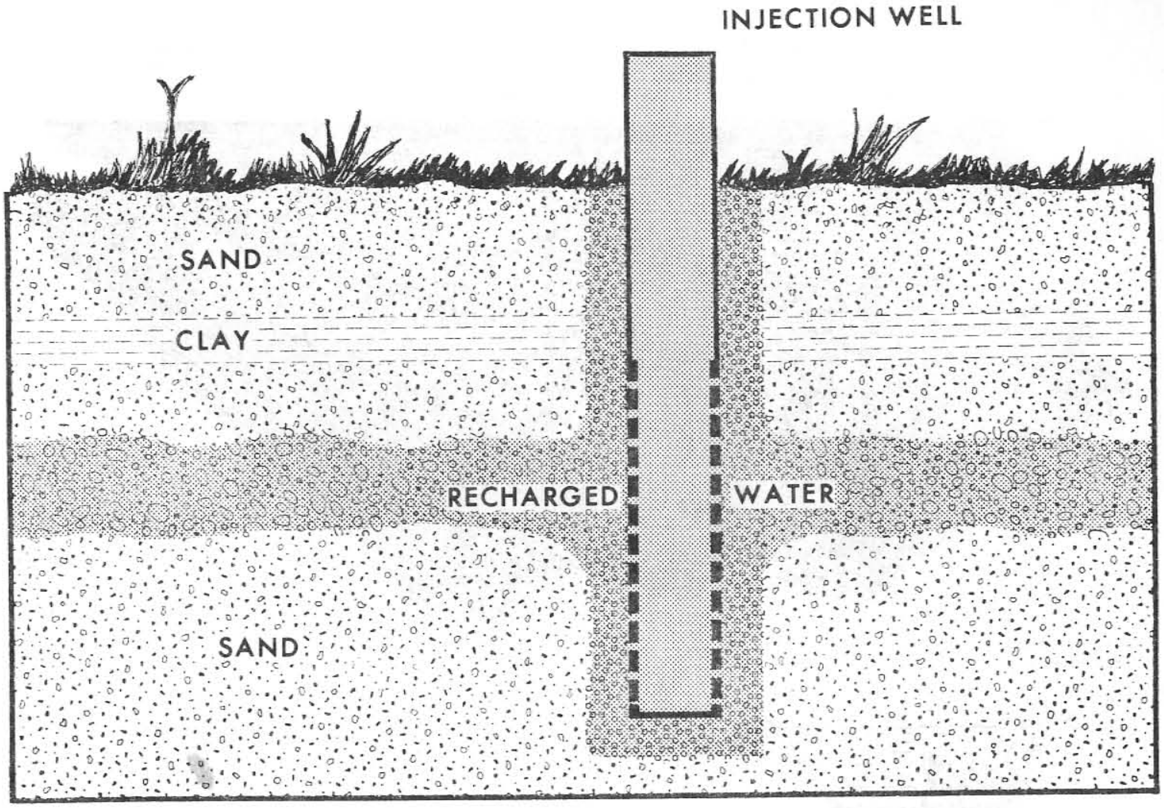


Figure 12.—Section at a Site Suitable Only for Artificial Recharge Through an Injection Well

would move rapidly to the water table where it would be available for pumping.

Artificial recharge through an injection well is most successful under the following conditions: (1) The recharge zone contains clean coarse gravel (pea-size or larger) or contains secondary solution openings; (2) the recharge water contains a very low concentration of suspended sediment; (3) air entrainment is prevented; and (4) high recharge velocities are maintained in operation of the injection well.

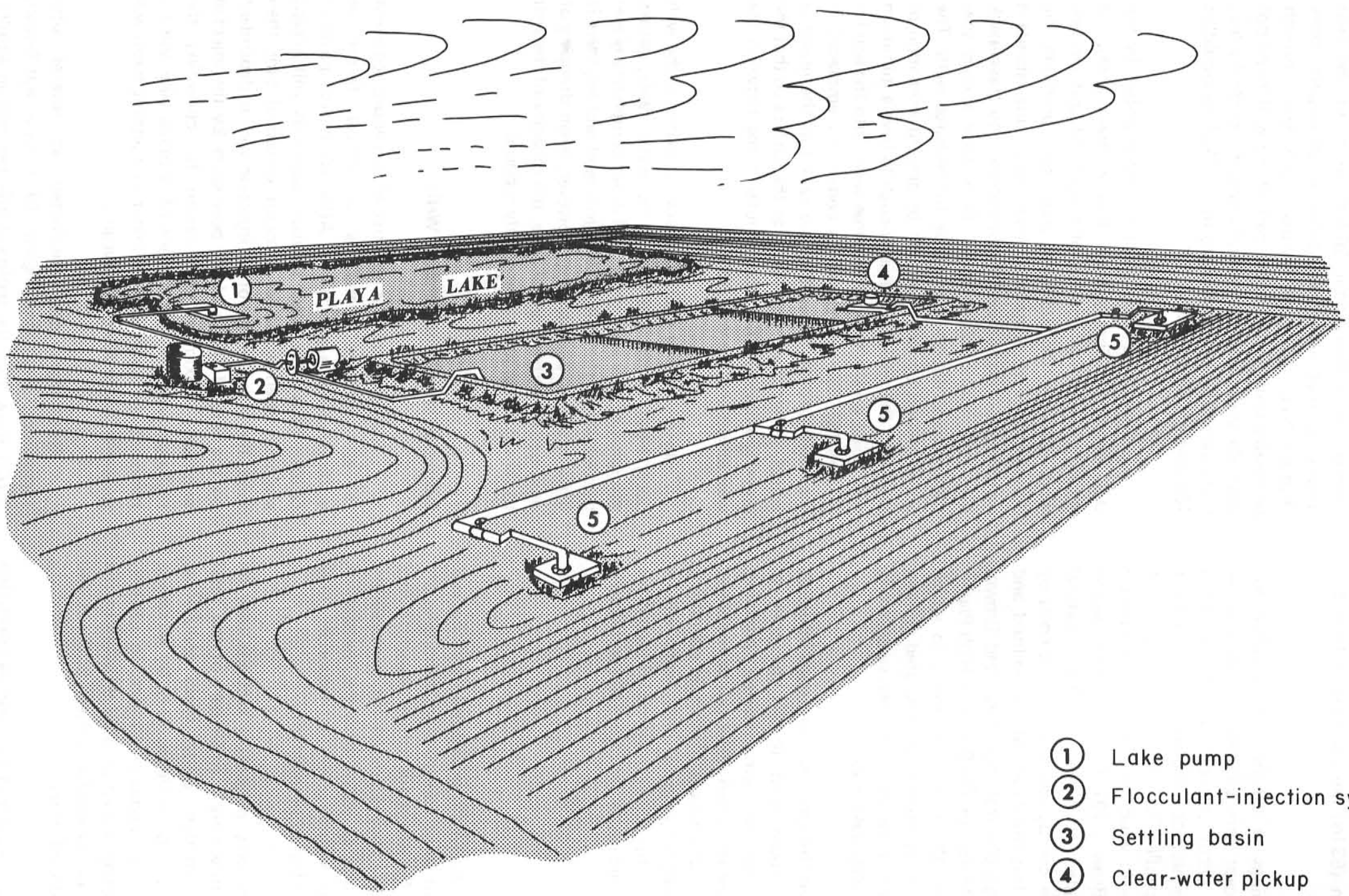
An idealized injection-well system is shown on Figure 13. A floating intake system obtains water from the surface of a playa lake. The water is transmitted through a pump, where a chemical flocculant is added to a settling basin where the sediment is allowed to settle. Water from the discharge end of the settling basin is pumped under positive pressure directly to an injection well. Additional injection wells are located near the settling basin so that recharge may continue if the first well becomes plugged.

Site Selection

Successful recharge of playa-lake water by use of injection wells requires that the wells penetrate zones that have high horizontal permeability, such as thick sections of clean coarse gravel or layers of caliche that have extensive solution openings. Clean gravel that is pea-size or larger will readily accept turbid playa-lake water; whereas, sections of sand will clog after only a few hours of injection of water of the same turbidity. The injected water should be clarified, however, even if highly permeable zones are present to minimize plugging of the aquifer with sediment.

Clean gravel can usually be identified in a well from a single-point resistance electrical log. Natural-gamma logs or neutron logs will provide additional information on factors relating to permeability (Keys and Brown; 1971, 1973). Zones of coarse gravel are closely associated with some major stream-valley systems on the pre-Ogallala surface. These valleys can generally be identified from maps that delineate this buried surface (Cronin, 1969).

Rayner (1967) points out that the area of the High Plains north of a boundary delineated by the buried Cretaceous escarpment along the northern Lubbock County line, and then northwest to the midpoint of the western Bailey County line is underlain by a part of the Ogallala Formation that has geologic and hydrologic characteristics more favorable for artificial recharge than



1. Lake pump
2. Flocculant-injection system
3. Settling basin
4. Clear-water pickup
5. Recharge wells

Figure 13

Idealized Injection-Well Installation With Water-Intake Systems (Lake Pump and Clear-Water Pickup), Flocculant-Injection System, and Settling Basins

in the formation south of this boundary. In general, areas in which well yields were initially greater than about 1,000 gal/min (63 l/s) are particularly favorable for artificial recharge.

Solution openings in caliche and in calcareous sand, which can accept large volumes of turbid water without plugging, occur throughout the Ogallala Formation; but the genesis of these openings has not yet been sufficiently studies to develop a means of identifying the areas in which they occur. Preliminary studies (Keys and Brown, 1971) indicate that caliche zones may be related to zones of higher natural radioactivity. Caliche can be identified in test holes by sampling, by noting lost circulation of drilling fluid, and by examination of geophysical logs (Keys and Brown, 1973). In several field tests on the Southern High Plains, caliche zones 10 feet (3 m) or more thick, in which horizontal hydraulic conductivity was estimated at more than 200 ft/d (61 m/d), have been recharged successfully with sediment-laden playa-lake water.

Water recharged through a dual-purpose irrigation and injection well would tend to fill the cone of depression formed by the well during pumping; therefore, most of the recharged water can be recovered by the well even after long periods of time. In operations in which a well is used for recharge only, water will be available for recapture for a longer period of time if the injection well is situated upgradient from the withdrawal well.

Well Construction

The optimum design of an injection well has not been determined, but some construction techniques are conspicuously more successful than others. Any construction technique that decreases the permeability of the formation, such as occurs with the invasion of drilling mud or the slumping of fine materials, may result in a permanent loss of permeability.

At many sites, very permeable sections may be thin or may constitute only a small part of the total thichness of the formation. Under these conditions, maximum recharge can be achieved only by screening wells in all of the very permeable zones. In general, screens or slotted casing should be used throughout the full thickness of the permeable zones, both in the saturated and unsaturated zones.

In many areas, the parts of the Ogallala Formation that are most favorable for artificial recharge are relatively thin zones above the water table. When these zones are cased-off or cemented, the rate at which water can be recharged through a well is greatly reduced. Normally, a gravity-flow recharge well should be screened to within about 20 feet (6 m) of the land surface so that water may enter all permeable zones (Figure 14). Although water recharged through permeable units in the upper part of the well might not reach the water table for several years, it is generally true that nearly all water recharged to the Ogallala would be available for repumping.

Cuttings and cores from test holes drilled by the U.S. Geological Survey show that in many areas, the Ogallala Formation consists of friable and uniform fine sand. Because the uniform grain size prohibits the development of a natural gravel-pack, the standard method of irrigation-well construction is to gravel-pack the well during completion. Tests have shown that similar construction is effective for recharge wells. The gravel should be small enough to prevent migration of sand into the well, but large enough to have a minimum restriction on the flow of recharge water into the aquifer (Figure 15). The gravel-pack is commonly emplaced in the well through pipes that are raised as the gravel is added, rather than shoveled in at the surface so that the gravel completely fills the annular space between the well screen and the well bore.

In a recharge well, agitation of water in the well bore, both above and below the water table, causes slumping of fine sand if the well is not completely gravel packed. When slumping occurs in a sand section, there is little effect on permeability; however, when slumping of sand occurs across a gravel zone, the capacity of the well to accept recharge may be greatly reduced.

Operation and Maintenance of Wells

The character and quantity of suspended sediment in the injected water is a critical factor in artificial-recharge operations. Although coarse gravel or caliche beds that have solution openings will accept sediment-laden water for a longer period of time than sand, the ultimate life of an injection well is dependent on the rate of filling of the pore space by the injected sediment. Maximum clarification by collecting the recharge water at the surface of a playa lake and by removing the suspended sediment in a settling basin will minimize the problem of plugging.

Recharge tests conducted at several sites (Schneider, Jones, and Signor, 1971; Keys and Brown, 1973) show that the sediment injected into an aquifer, even in a zone of fine sand, moved a considerable distance away from the recharge well into the aquifer. Redevelopment of these wells by pumping and surging

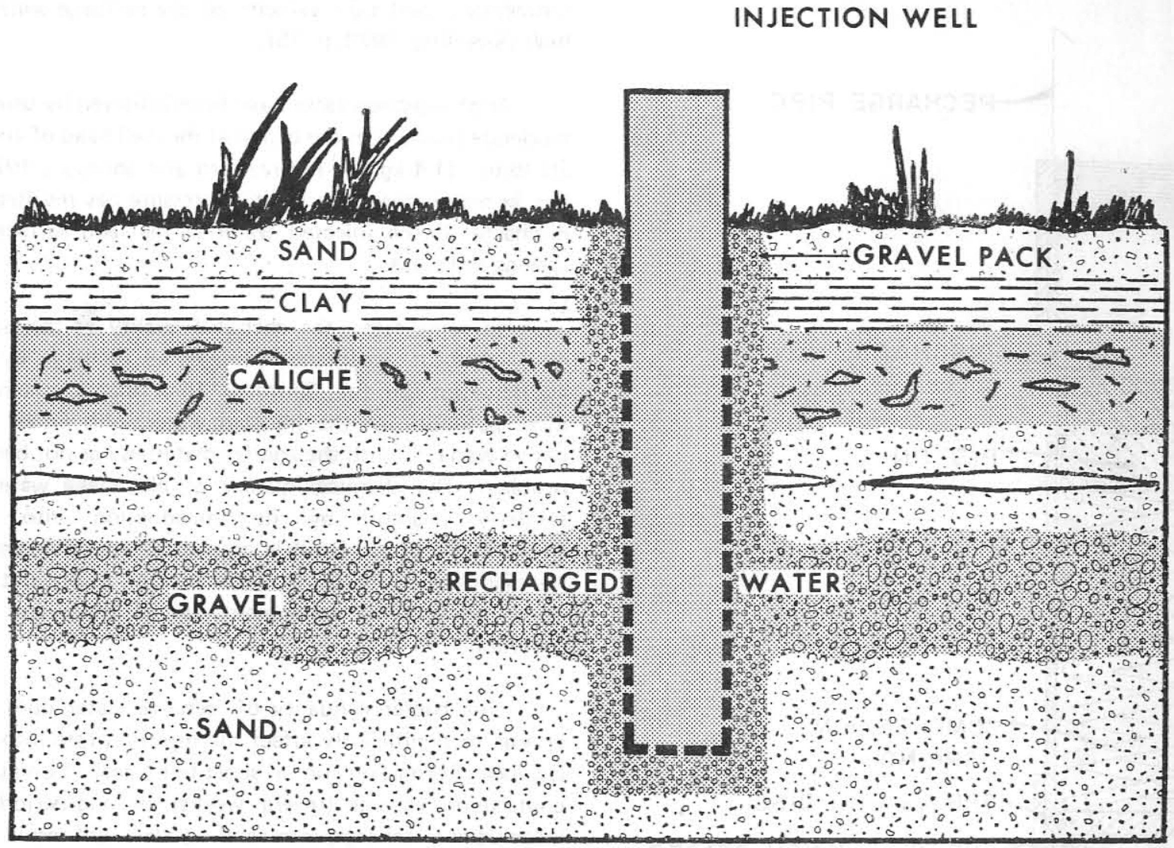


Figure 14.—Injection Well Screened to Permit Maximum Recharge Through an Upper Section of Caliche and a Lower Section of Coarse Gravel

did not remove a measurable part of the sediment that was deposited 6 feet (1.8 m) or more from the injection well. Probably the effect of redevelopment of a well is greater in clean coarse gravel than in fine sand, but the results of these tests indicate that redevelopment of a well by pumping and surging cannot assure reestablishment of the initial permeability of the formation.

Recharge water that contains a high percentage of dissolved and entrapped air (air entrainment) has long been recognized as a potential problem in recharge operations (Sniegocki and Reed, 1963). Freefall of water into a well or negative pressures at any point within a recharge system may result in air entrainment, which clogs an aquifer system rapidly because the small air bubbles effectively block the pore spaces and prevent or restrict further movement of the recharged water.

To prevent air entrainment, the recharge water should be injected at such a rate that positive pressure is continually maintained in the injection pipe, or the water should be injected through a pipe that has a valve at the bottom to maintain positive pressure during injection. By using such a valve, positive pressure will be maintained on the water at all times, regardless of the rate of flow. A pressure-actuated valve used successfully in experimental recharge tests by the U.S. Geological Survey is shown on Figure 16.

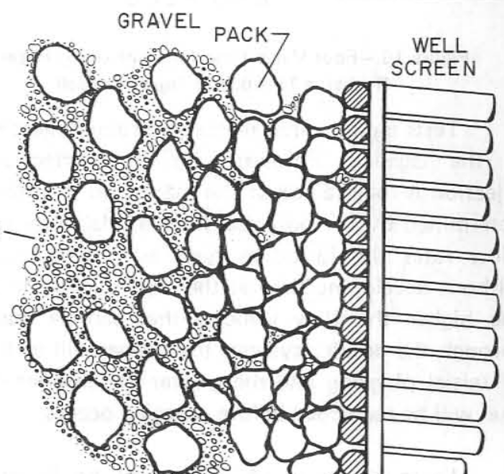


Figure 15.—Function of a Gravel Pack in Retarding the Migration of Fine Sand to a Well Screen

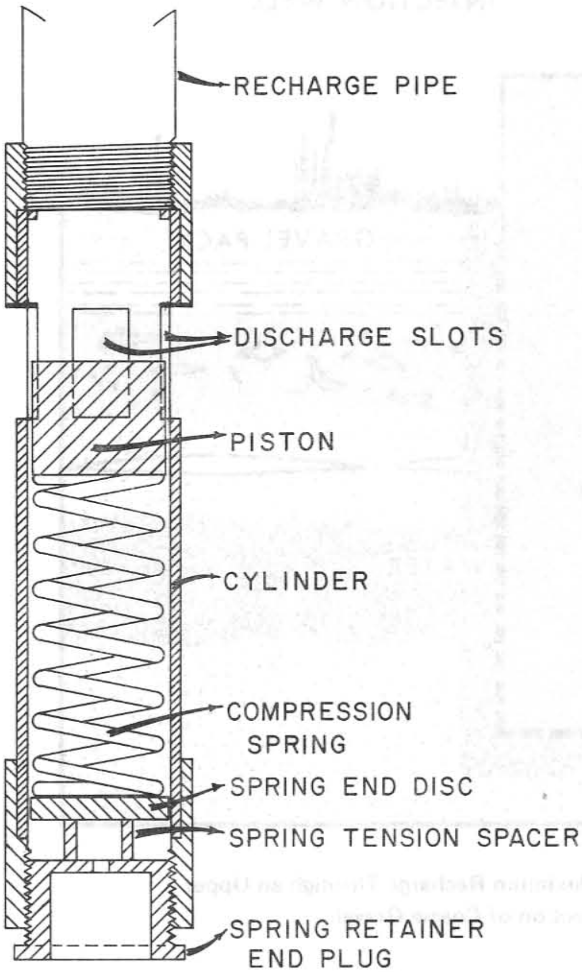


Figure 16.—Foot Valve Used for Controlling Rates of Recharge Through an Injection Well

Tests indicate that recharge through injection wells in the Ogallala Formation is most effective when injection is maintained at the maximum possible rate as determined by the potential head available for recharge. Flow rates should be as high as can be maintained without developing flow at the land surface. In general, the higher the flow velocity that can be maintained through the aquifer system, the deeper will be the point of initial plugging and the greater the amount of water that will be recharged before plugging occurs.

Large amounts of water can be injected into carbonate-rock zones in the Ogallala Formation because the solution openings in these zones are large and well connected and because playa-lake water is an effective solvent of calcium carbonate. As a result of the solution of calcium carbonate by the recharged water, the pore volume in these caliche zones is continually increased during recharge. The rate of solution is dependent on many factors, but tends to be most rapid when the temperature and flow velocity of the recharge water is high (Sweeting, 1973, p. 35).

High injection rates have been achieved by using a moderate pressure in the casing at the well head of about 20 lb/in^2 (1.4 kg/cm^2) (Crawford and Johnson, 1973), but in many areas, this positive pressure has resulted in discharge of the injected water at the land surface as springs and seeps.

In some areas, the chemical quality of the water may limit the acceptance of injected recharge by an aquifer, but on the Southern High Plains, chemical incompatibility of the injected water with either the native water or with the aquifer materials has not been a problem. The chemical quality of playa-lake water is slightly changed by its introduction into the environment of the Ogallala aquifer, but the changes are not significant in terms of the formation of precipitates or of limiting the subsequent use of the water for irrigation.

The bacterial quality of recharge water does not appear to significantly affect the injection rate into the Ogallala Formation on a short-term test. Long-term continuous recharge (several weeks), or long periods of intermittent recharge, into sand aquifers will result in a reduction in the recharge rate because of the growth and accumulation of anaerobic bacteria adjacent to the well bore. The wells will regain much of their initial capacity if they are treated with oxidizing agents. Bacteria can travel considerable distances through the solution openings in caliche zones and through clean coarse gravel. During recharge tests, bacteria have been collected more than 100 feet (30 m) from a recharge well.

The life expectancy of an injection well on the Southern High Plains cannot be predicted accurately from the tests that have been conducted so far. Several wells have received more than 100 acre-feet (123,300 m^3) of recharge water during a 2-year period at rates in excess of 500 gal/min (31.5 l/s) and are still capable of receiving more water at this rate.

SEDIMENT FLOCCULATION

A very effective method of decreasing the concentration of suspended sediment in water is by chemical treatment that causes aggregation of fine particles into floc or large heavy particles. The relatively heavy floc sinks quickly to the bottom of a reservoir, leaving the water relatively clear and free of sediment.

The most commonly used flocculant in water-treatment plants is aluminum sulfate or alum. Other flocculants include ferric chloride ($FeCl_3$) and complex organic compounds called polyelectrolytes. Tests were made with a large number of flocculants, but new ones are continually being offered on the market that may prove to be superior for use in removing the sediment from playa-lake water. The following data should be used only as a guide to the choice of flocculants.

To evaluate many of the available flocculants, a series of experiments was made in the laboratory to compare the effectiveness of the types and concentrations of flocculants in water collected from playa lakes in drainage basins with various soil types. Water samples were collected from eight playa lakes (Figure 17) shortly after several periods of rainfall in May 1974. Flocculation tests were started soon after the samples were collected and were continued for approximately 1 month. Repetitive tests indicated that there were no water-quality changes in the samples during the test period that would affect flocculation. The graphs on Figures 18a-h show the results obtained under optimum laboratory conditions. The results obtained through the use of the flocculants under actual field conditions could vary considerably from the results obtained in the laboratory tests.

The effectiveness of flocculation in removing sediment from playa-lake water can be determined by the filterability of the water samples. The filterability of the treated water samples was as much as 100 times greater than the filterability of untreated samples. The comparative filtration values (using a 0.45-micrometer filter and a constant vacuum) of treated and untreated samples of water collected from the playa lakes are given in the following table:

	Filtration time	
Lake	Treated samples	Untreated samples
Harrist	8.4 sec.	3 min., 31 sec.
Reynolds	8.5 sec.	6 min., 36 sec.
Dawson	9.0 sec.	19 min., 40 sec.
Fullingim	8.0 sec.	4 min., 1 sec.
Roberson	8.4 sec.	8 min., 11 sec.
Kinard	8.7 sec.	3 min., 55 sec.
Boozer	9.0 sec.	21 min., 15 sec.
Dunlap	8.2 sec.	2 min., 56 sec.

Field tests conducted on water samples from Dalton's playa lake, north of Petersburg, Texas, show that flocculants can be successfully injected through the intake hose of a water pump. A mixture of cationic polyelectrolyte and ferric chloride ($FeCl_3$) was metered into the lake-pump inlet at a rate to add 40 mg/l ferric chloride and 8 mg/l polyelectrolyte to the pumped water. The centrifugal pump used to take water from the lake was operated at a speed sufficient to pump 200 gal/min (12.6 l/s) against 5 feet (1.5 m) of head. Mixing was achieved in passage through the pump impellers. Floc building occurred in a 50-foot (15.2-m) by 5-foot (1.5-m) settling basin in which the water depth was maintained at about 3 feet (0.9 m).

Water entered the settling basin vertically through a series of four 2-inch (51-mm) holes drilled into the top of a capped 6-inch (152-mm) plastic pipe (Figure 11). Turbulence created by the vertical jets of water through these orifices created floc-building conditions comparable to paddle-stirrer agitation in the laboratory. The large floc settled rapidly at the inlet end of the settling basin and was effectively prevented from migrating to the outlet end by a window-screen barrier. The initial sediment load in the water at this location was 4,700 mg/l, and the final sediment load was less than 10 mg/l.

A laboratory comparison of the time required for clarification of flocculated and unflocculated water shows the effectiveness of flocculants in reducing turbidity. A playa-lake sample having 160 mg/l suspended sediment was chosen as an example. Part of the sample was flocculated by using 1 mg/l of Nalco 607 and 4 mg/l of liquid alum. The treated and untreated samples were individually mixed with a paddle stirrer, and the results were as follows:

Treated samples		Untreated samples	
Time, in min.	Turbidity	Time, in min.	Turbidity
2	49	2	150
5	26	5	140
10	14	10	140
15	14	15	135

COST ANALYSIS OF ARTIFICIAL-RECHARGE SYSTEMS

The design of an artificial-recharge system should be based on a combination of geohydrologic principles and economics. The cost of constructing a recharge facility depends to a large extent on the equipment and manpower that is available. Although certain fixed costs, such as the costs of pumps, pipe, and chemical

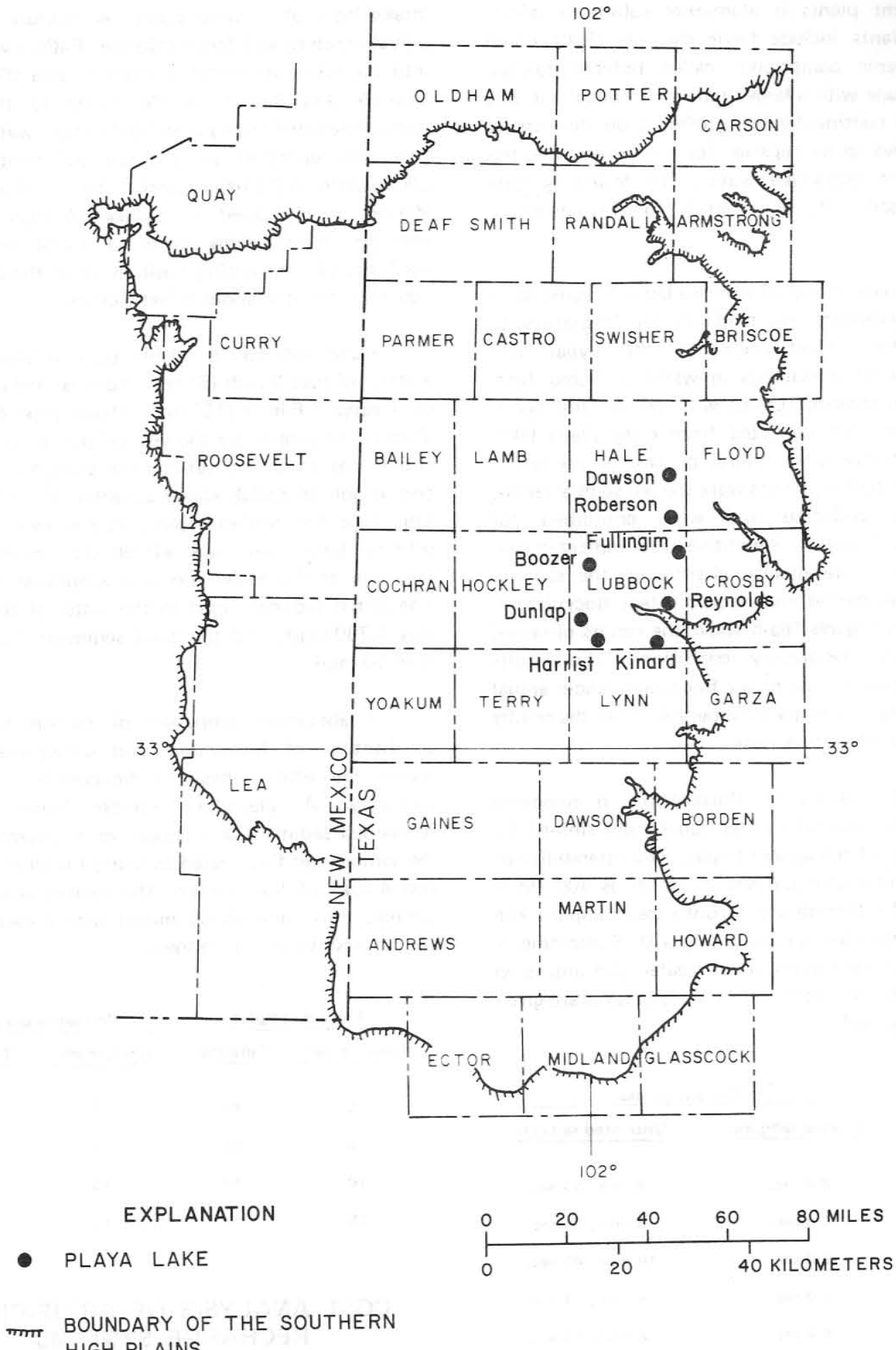


Figure 17

Locations of Playa Lakes From Which Water Samples Were Collected for Flocculation Tests

Base from U.S. Geological Survey State base map, 1: 1,000,000

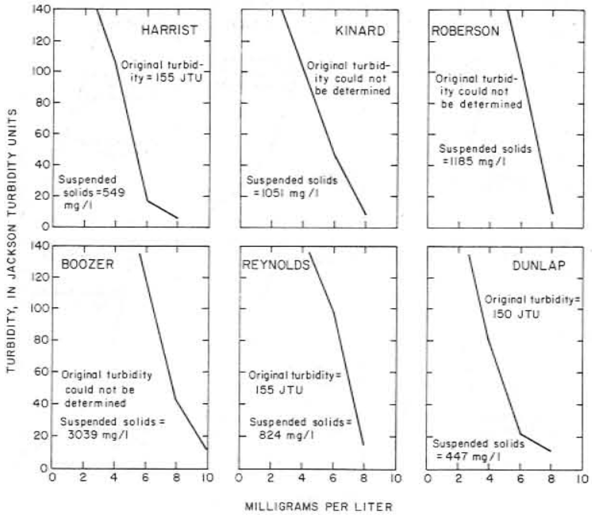


Figure 18a.—Turbidity Reductions Obtained by Use of Polyelectrolyte Flocculants; Rohm and Hass Prima Flocculant C-7

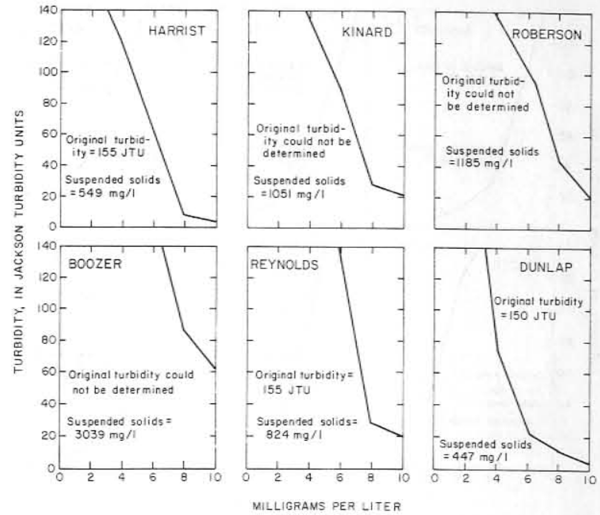


Figure 18c.—Turbidity Reductions Obtained by Use of Polyelectrolyte Flocculants; Nalco 600

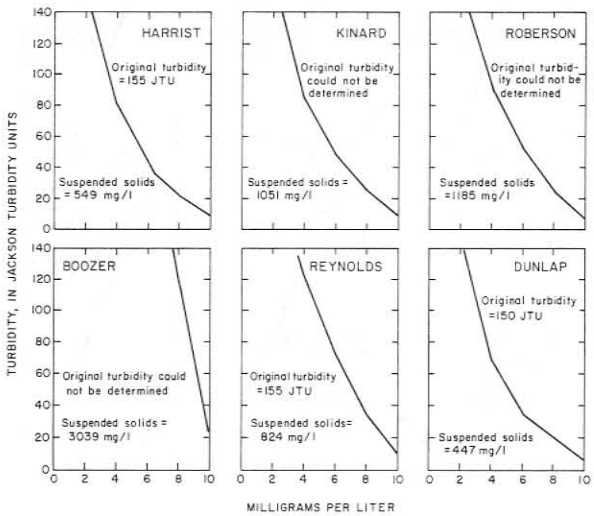


Figure 18b.—Turbidity Reductions Obtained by Use of Polyelectrolyte Flocculants; Jaguar 22-A, Stein Hall, Inc.

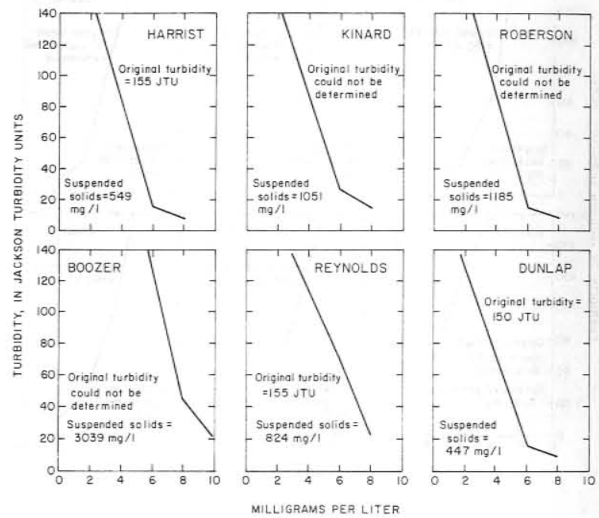


Figure 18d.—Turbidity Reductions Obtained by Use of Polyelectrolyte Flocculants; Union Carbide X-150

flocculants, can be determined accurately, the construction and operating costs are more difficult to estimate.

The determination of geohydrologic factors is dependent upon the basic data available. The most relevant data include core samples or drill cuttings from the geologic section through which recharge will take place; pumping-test or recharge-test results from which permeability values can be computed; and data on the suspended-sediment, dissolved oxygen, and biodegradable organic carbon contained in the recharge water. The cost of acquiring the needed data can be estimated from local drillers' charges for test holes and aquifer tests, and from laboratory charges for water-quality analyses.

The volume of water that is available for recharge can be estimated from the area of the watershed that drains into the playa lake. An approximation of the amount of runoff into the lake can be made by assuming that in a year with less than normal precipitation, 0 to 1 inch (25 mm) of the rainfall may become runoff. In years when rainfall is greater than normal, half of the rainfall above the normal amount may become runoff (Figure 19). Table 1 gives precipitation and runoff data for selected playa lakes.

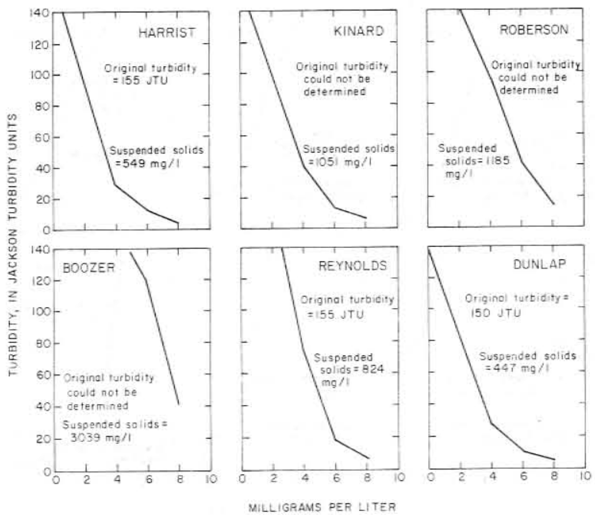


Figure 18e.—Turbidity Reductions Obtained by Use of Polyelectrolyte Flocculants; Nalco 607

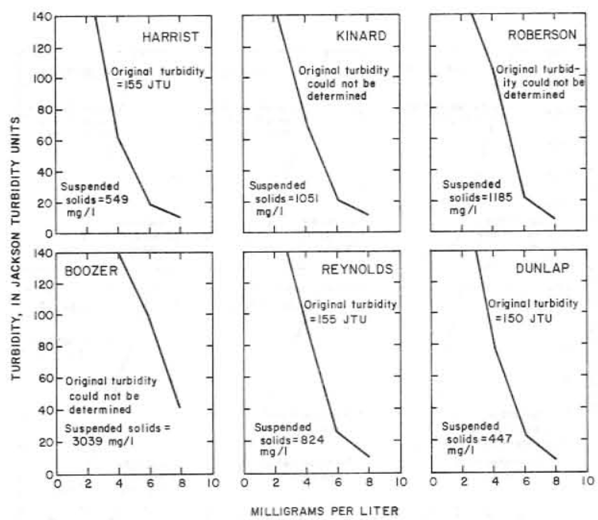


Figure 18f.—Turbidity Reductions Obtained by Use of Polyelectrolyte Flocculants; Nalco 8101

If a drainage basin has an area of 500 acres (202 hm^2) and an average annual rainfall of 18 inches (457 mm), and if rainfall for an assumed wet year is 10 inches (254 mm) more than normal, or 28 inches (711 mm), about 5 inches (127 mm), or 208 acre-feet (256,000 m^3) of water may flow into a playa and become available for artificial recharge. In a year with less than normal rainfall, such as 15 inches (381 mm), 0 to 42 acre-feet (0 to 51,800 m^3) may be available.

If under ideal conditions, it is assumed that: (1) The amount of runoff available for recharge is 100 acre-feet (123,300 m^3); (2) the average infiltration rate in the spreading basin is about 2 ft/d (0.6 m/d); and

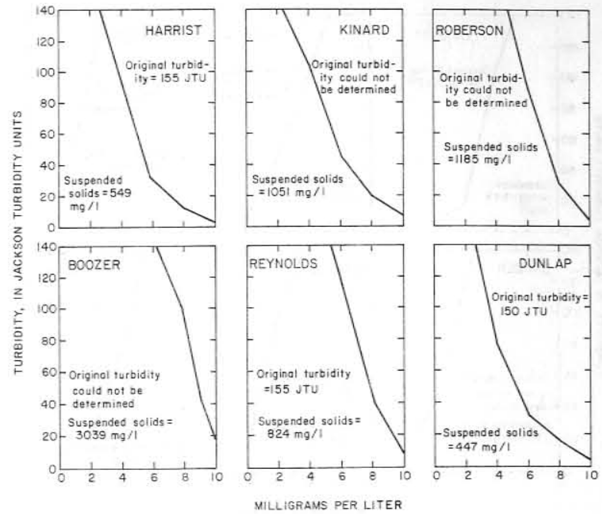


Figure 18g.—Turbidity Reductions Obtained by Use of Polyelectrolyte Flocculants; Nalco 8113

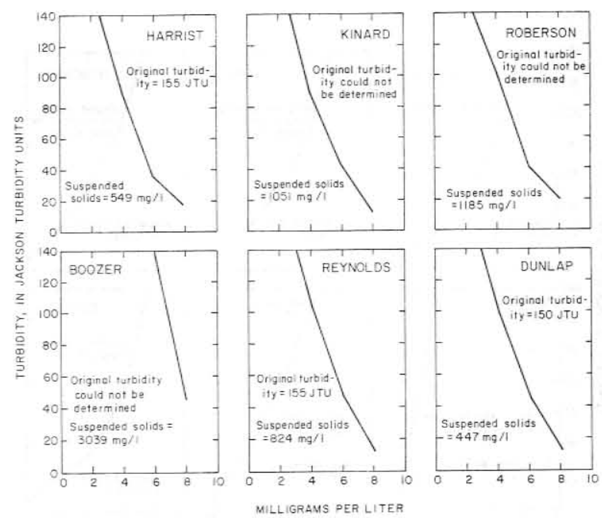


Figure 18h.—Turbidity Reductions Obtained by Use of Polyelectrolyte Flocculants; Rohm and Hass Prima Flocculant C-5

(3) the pumps used to obtain water from the lake yield 1,000 gal/min (63 l/s), then recharge of the water could be accomplished in 3 to 4 weeks.

The design of a spreading-basin system that includes water-treatment and clay-settling processes can be facilitated by use of the data shown on Figure 20. Note that in Figure 20 there are four labeled scales: (1) Inflow rate on the left; (2) retention time multiplied by inflow rate on the right; (3) infiltration rate multiplied by area on the bottom; and (4) settling basin cross-sectional area multiplied by length on the top. Curve no. 1 uses the left and bottom scales, and curve no. 2 uses the top and right scales. The following

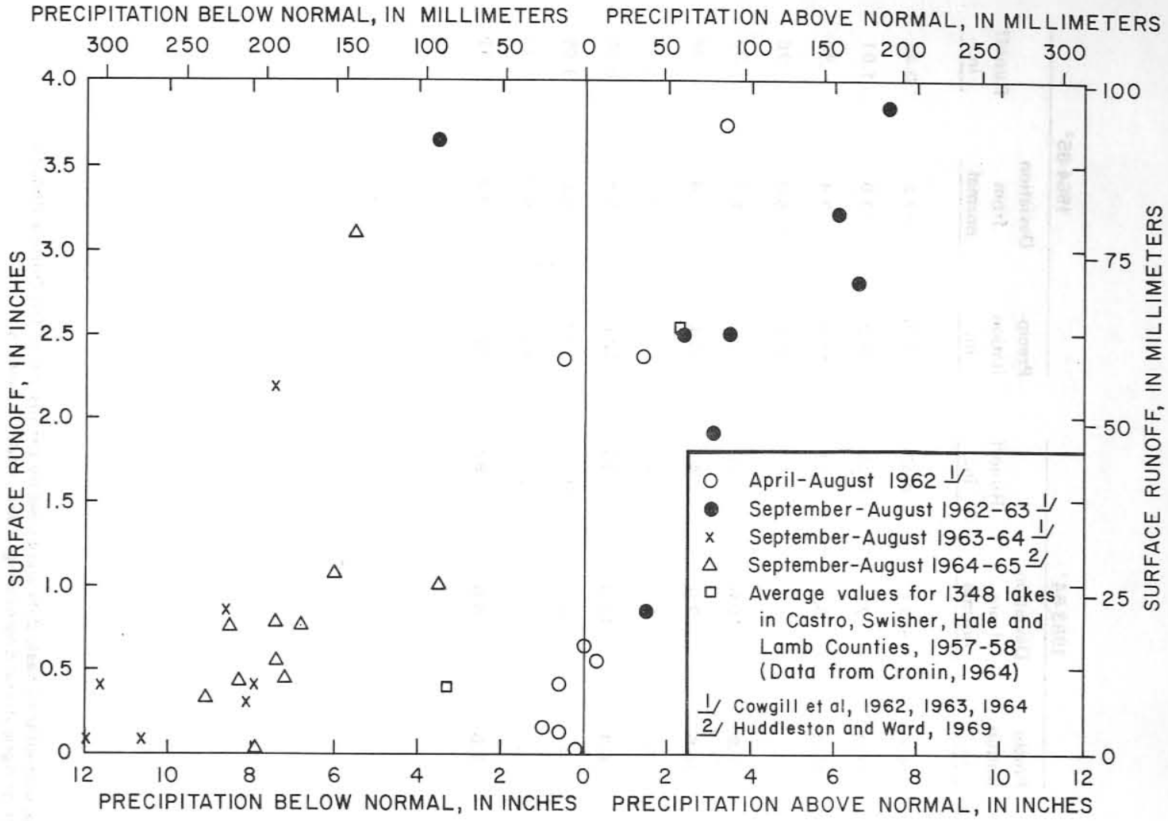


Figure 19.—Runoff Into Playa Lakes in Relation to Rainfall

examples under the stated conditions show how these curves can be used in designing a spreading basin.

From the prior assumption that the infiltration rate for basins in the area is about 2 ft/d (0.6 m/d) and the available pump has a capacity of 1,000 gal/min (63 l/s), curve no. 1 is used by finding 1,000 gal/min (63 l/s) on the inflow-rate scale on the left, proceeding to the curve to the right and then down to the scale of infiltration rate multiplied by basin area, where a value of 192,000 is read. Because 2 ft/d (0.6 m/d) is the infiltration rate to be expected, 192,000 divided by 2 equals the required area of the basin.

$$\text{Basin area} = \frac{192{,}000 \text{ ft/d X ft}^2}{2 \text{ ft/d}} = 96{,}000 \text{ ft}^2$$

(8,918 m^2), which is 2.2 acres.

Figure 20 is also used for calculating the size of a settling basin. For example, the water is to be treated for removal of suspended sediment and this process requires 3 hours of flow-through or retention time in a settling basin. The pumping rate or inflow rate is 1,000 gal/min (63 l/s).

Retention time in hours multiplied by inflow rate in gal/min is:

$$3 \text{ X } 1{,}000 = 3{,}000$$

Find 3,000 on the scale of retention time multiplied by inflow rate and move left to curve no. 2, then up to the scale of settling basin cross-sectional area multiplied by length, where a value of 24,000 is read. The settling basin can then be constructed according to the requirement of either length or cross-section area. Assume that the settling basin can be readily built 30 feet (9 m) wide and 10 feet (3 m) deep. The cross section is then 300 square feet (27 m^2) and the basin length is:

$$\frac{24{,}000 \text{ ft}^2 \text{ X ft}}{300 \text{ ft}^2} = 80 \text{ ft } (24.4 \text{ m})$$

Figure 21 is a diagram showing the cost factors (1975) of an artificial-recharge installation. No total costs are shown because variations in the scheme, inclusion or exclusion of various components, or additional modifications to the lake would change the totals. If the topography is suitable, gravity flow in any phase of the operation will reduce the number of pumps required. A minimum specification of components is noted only to relate to costs; the individual situation would dictate actual requirements.

Recharge through injection wells requires a pipe to conduct water from the surface down the well to the water table. To prevent air entrainment, either a foot valve (Figure 16) or a limited-size pipe is used to

Table 1.—Precipitation and Runoff Data For Selected Playa Lakes

Lubbock County[1]

Lake name	1962[2]			1962-63[3]			1963-64[3]			1964-65[3]		
	Precip-itation in.	Deviation from normal	Runoff in.	Precip-itation in.	Deviation from normal	Runoff in.	Precip-itation in.	Deviation from normal	Runoff in.	Precip-itation in.	Deviation from normal	Runoff in.
Huckabee	—	—	0	19.9	+1.5	0.86	6.8	−11.6	0.42	11.2	−7.2	0.46
Knowles	10.5	−0.6	0.42	24.5	+6.1	3.23[4]	11.0	− 7.4	2.20	14.9	−3.5	1.01
Hufstedler	10.1	−1.0	.16	25.0	+6.6	2.82	10.3	− 8.1	.31	11.0	−7.4	.56
L.C.C.	11.4	+ .3	.57	17.9	− .5	2.36	—	—	—	11.6	−6.8	.76
Kitten	14.5	+3.4	3.75	25.7	+7.3	3.86	7.8	−10.6	.09	9.3	−9.1	.33
Holland	10.5	− .6	.13	21.9	+3.5	2.52	10.5	− 7.9	.42	11.0	−7.4	.78
Cooper	12.5	+1.4	2.37	—	—	—	—	—	—	—	—	—
Burgett	—	—	—	20.4	+2.0	3.99	6.4	−12.0	.10	12.9	−5.5	3.10
Cox	—	—	0	20.8	+2.4	2.52	—	—	0	12.4	−6.0	1.08
Dupree	11.1	.0	.65	21.5	+3.1	1.92	—	—	0	10.1	−8.3	.43
Krueger	—	—	—	14.9	−3.5	3.66	9.8	− 8.6	.87	10.5	−7.9	.12

Castro, Swisher, Hale, and Lamb Counties[5]

	1957			1958		
	Precip-itation in.	Deviation from normal	Runoff in.	Precip-itation in.	Deviation from normal	Runoff in.
Composite of 1,358 lakes	23.13	+2.30	2.54	17.54	−3.29	0.41

[1] Information taken from Cowgill and others, 1962, 1963, 1964; and Huddleston and Ward, 1969. Also, unpublished basic data were used by permission of Dr. Donald Reddell, formerly Hydrologist, High Plains Underground Water Conservation District No. 1, presently Professor of Agricultural Engineering, Texas A&M University.

[2] Data are from April-August 1962. Normal precipitation for April through August from 1941-1970 is 11.13 inches.

[3] Data are from September to August. Average precipitation at Lubbock for calendar years 1941-1970 is 18.41 inches.

[4] Includes approximately 0.1 inch irrigation tailwater.

[5] Information taken from Cronin, 1964.

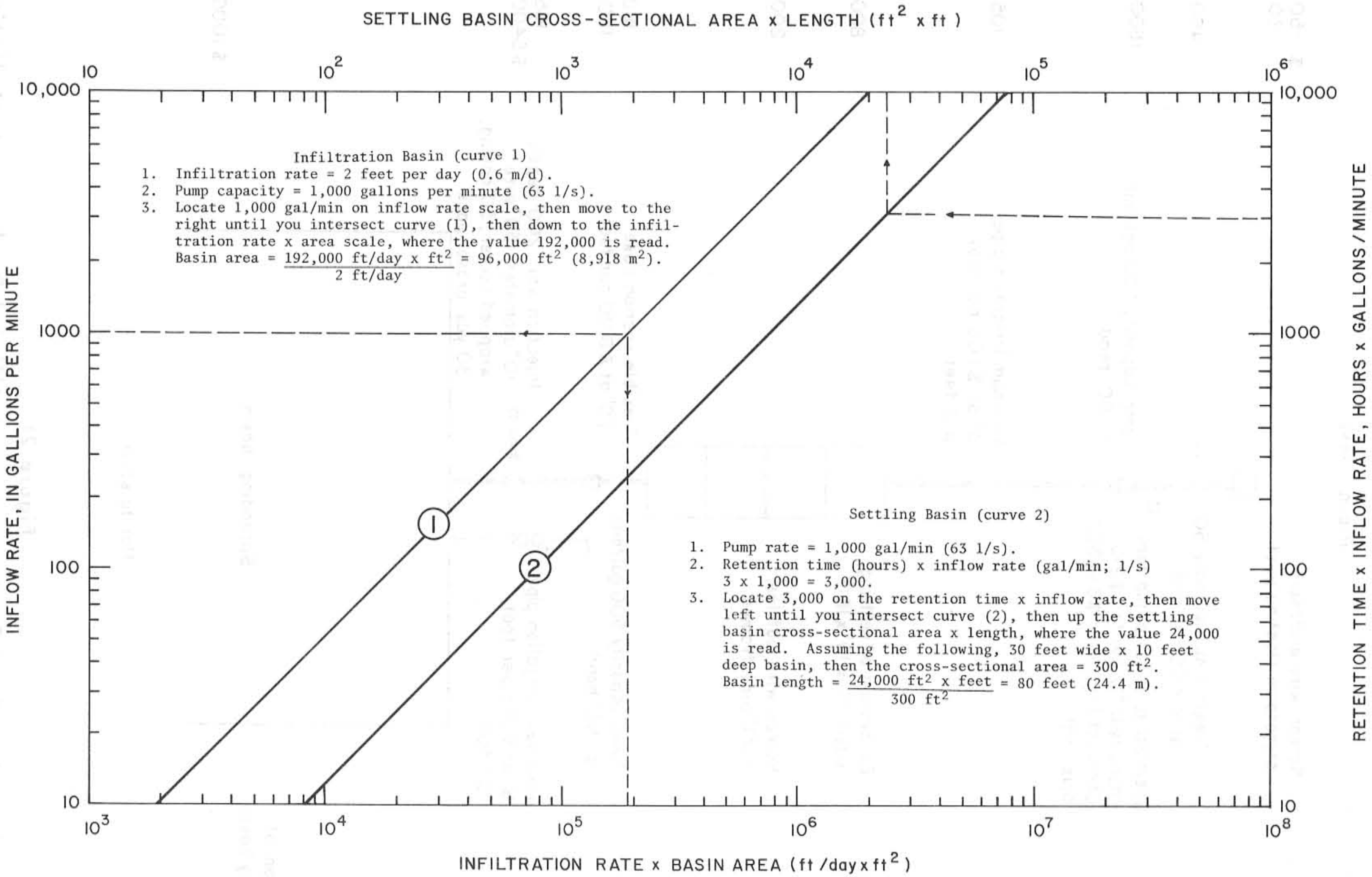


Figure 20

Graph for Determining the Dimensions of Spreading and Settling Basins

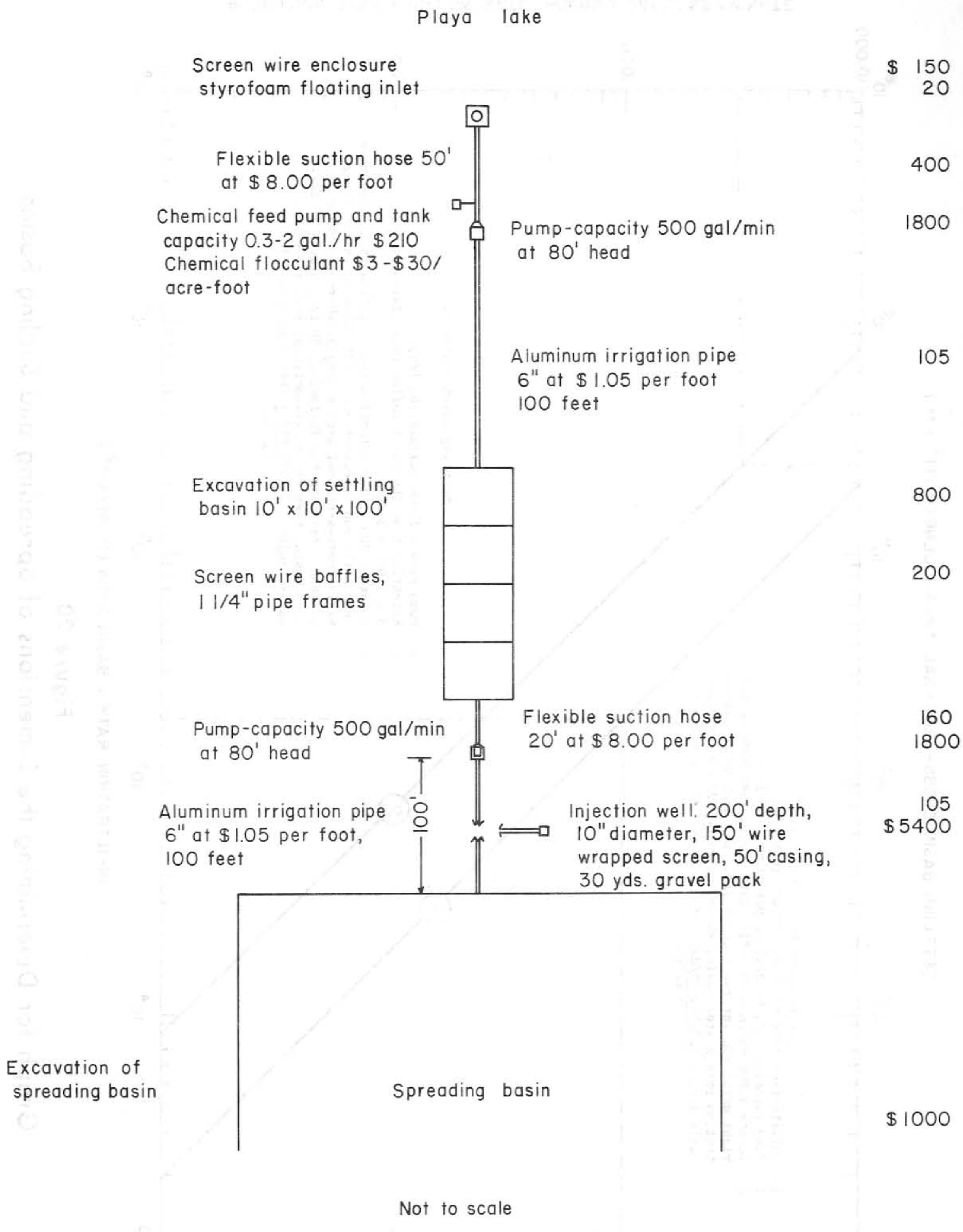
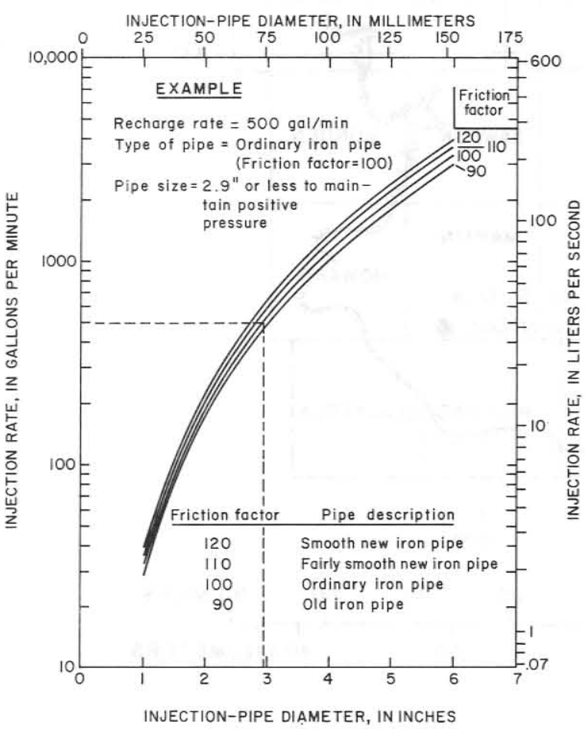


Figure 21
Diagram Showing Cost Factors of an Artificial-Recharge Installation

maintain positive pressure. The proper diameter of a recharge pipe for limiting flow can be determined from the data on Figure 22, which shows the minimum flow required to maintain positive pressure throughout the length of the recharge pipe. For example, if water were available to recharge 500 gal/min (32 l/s) through a well, and a supplier could deliver ordinary iron pipe that has a friction factor of 100, the pipe size could be selected by using Figure 22. The 500 gal/min (32 l/s) rate can be found on the left-hand scale. Moving across to the right to the curve marked 100 for the friction factor, and then down to the bottom scale, the pipe size required is shown to be about 2.9 inches (74 mm). Installing pipe with a diameter of 2.75 inches (69.85 mm) would insure positive pressure with a recharge rate over 440 gal/min (28 l/s). If a 3-inch (76-mm) pipe were selected, recharge would have to be maintained at about 530 gal/min (33 l/s) to insure positive pressure at the well head.

CASE HISTORIES OF ARTIFICIAL-RECHARGE OPERATIONS

Artificial-recharge operations have been conducted at several sites on the Southern High Plains. The following discussions give brief descriptions of some of the recent operations, and Figure 23 shows the locations of the sites. Other experiments are described or referenced in Brown and Signor (1973).



Modified after Reeder, 1975

Figure 22.–Graph for Determining the Proper Diameter of Injection-Well Pipe

Lubbock Airport Site

Water imported from Lake Meredith on the Canadian River was recharged through a 1-acre ($4{,}047\text{-m}^2$) basin northeast of Lubbock, Texas. The basin was excavated 1.5 feet (0.46 m) into Pleistocene sediment and surrounded by a 4-foot (1.2-m) berm. Water was recharged at this site continuously for 14 months. The initial rates of infiltration exceeded 1.5 ft/d (0.46 m/d), and the maximum rates were almost 3 ft/d (0.9 m/d). The total volume of water recharged was 580 acre-feet ($715{,}140\ m^3$). The recharge rate was reduced by the growth of anaerobic bacteria, but recharge continued to the end of the test through about 20 openings in the basin floor, each approximately 1 square foot ($0.09\ m^2$) in area, that were assumed to be old animal burrows enlarged by the flow of the recharge water.

Bushland Site

Two 0.1-acre (405-m^2) infiltration basins were constructed by removing the topsoil and exposing the Pleistocene sediments near Bushland, Texas. One basin was recharged with turbid playa-lake water; the other basin was recharged with well water. Infiltration of the turbid water was 147 vertical feet (45 m) in 65 days, at a maximum rate of 3.5 ft/d (1.1 m/d). Infiltration of the well water was 196 feet (60 m) in 46 days, at a maximum rate exceeding 7 ft/d (2.1 m/d). The test was conducted by the Agricultural Research Service of the U.S. Department of Agriculture (Aronovici, Schneider, and Jones, 1972).

Colorado River Municipal Water District

A total of about 4,000 acre-feet ($4.9 \times 10^6\ m^3$) of water was recharged through injection wells from December 1963 to July 1968, and recharge operations are continuing (1975). The recharge wells are in Martin County, Texas, and the water supply is from Lake J. B. Thomas, northeast of Big Spring in Borden and Scurry Counties. Each recharge period begins in late October and continues through March of the following year.

The lake water, which has an average sediment load of 20 to 25 mg/l is treated with chlorine to retain a residual concentration of 1.5 mg/l at the wellhead. The

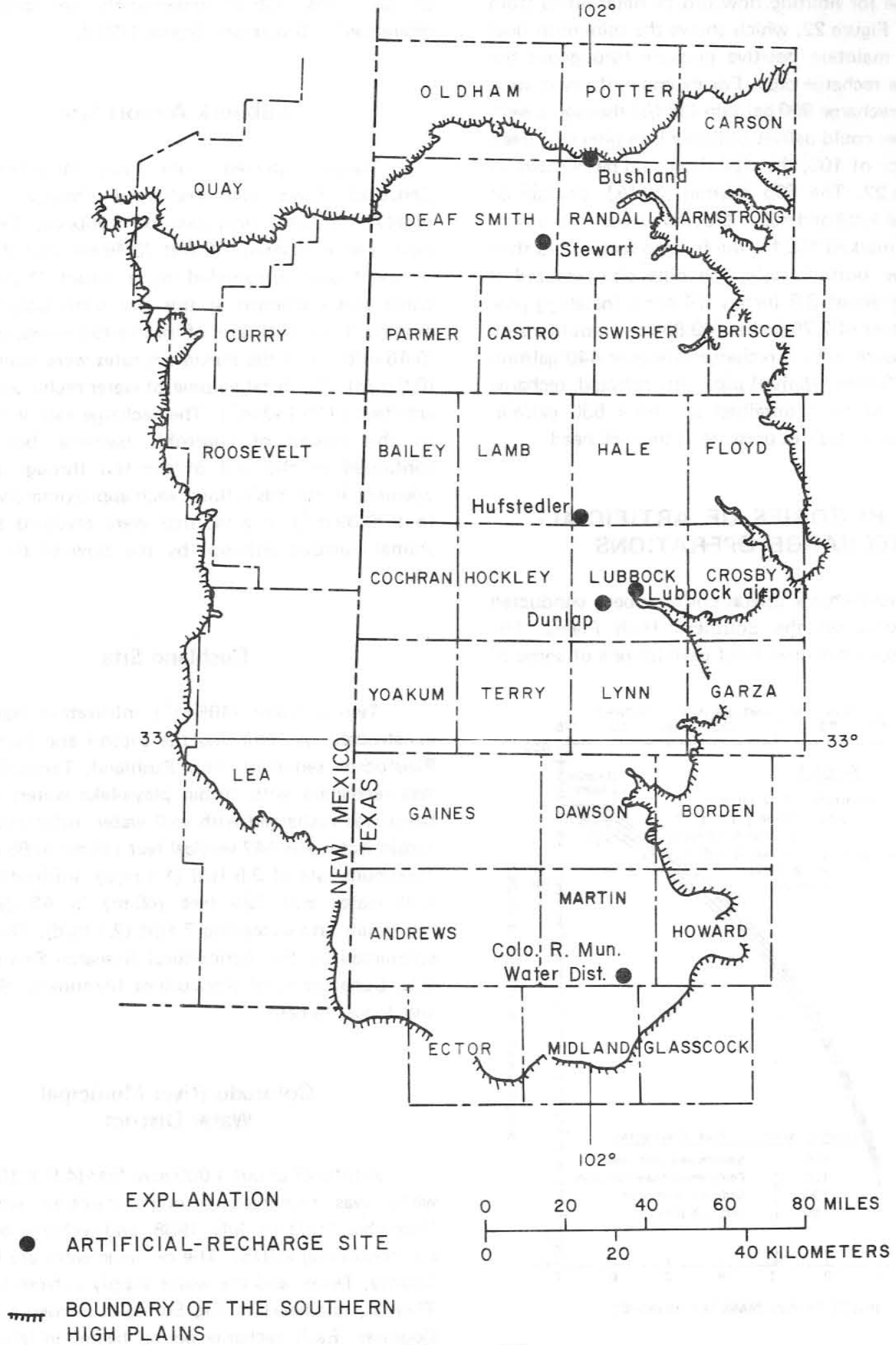


Figure 23

Locations of Artificial-Recharge Sites

Base from U.S. Geological Survey State base map, 1: 1,000,000

water temperature ranges from 3.3° to 22°C (38° to 72°F). The wells are surged and pumped 4 to 5 hours once every 7 days. Water from the wells is very turbid for a few minutes after initial pumping. Data were furnished by O. H. Ivie and W. P. Odom, Colorado River Municipal Water District, Big Spring, Texas (Brown and Signor, 1973).

Hufstedler Site

Turbid playa-lake water containing 550 to 600 mg/l of suspended sediment was recharged through a dual-purpose gravel-packed well into about 15 feet (4.6 m) of clean sand. Recharge was maintained at an average rate of 150 gal/min (9.5 l/s) for 21 hours. Pumping the well showed that the specific capacity of the well was reduced from 6.2 to 3.8 (gal/min)/ft [1.28 to 0.79 (l/s)/m]; subsequent development increased the specific capacity to 4.1 (gal/min)/ft [0.85 (l/s)/m]. Geophysical logs at the site indicated that deposition of injected sediment occurred 6 feet (1.8 m) from the recharge well and was not removed by pumping (Schneider, Jones, and Signor, 1971; Keys and Brown, 1973).

Dunlap Site

Playa-lake water that contained about 100 mg/l suspended sediment was injected under pressure into the Ogallala aquifer near Wolfforth, Texas. About 15 acre-feet (18,495 m^3) of water was injected at an average rate of 1,800 gal/min (114 l/s) under pressures ranging from 75 to 80 lb/in^2 (5.3 to 5.6 kg/cm^2). The recharge well was gravel-packed and torch-slotted from 70 feet (21 m) to 164 feet (50 m).

Plugging occurred in the lower sand section of the well, but there was little evidence of plugging in secondary solution openings in caliche at a depth of about 40 feet (12 m). The recharged water became perched above the water table, but within 1 year, most of the recharged water had infiltrated to the water table at a depth of 125 feet (38 m) (Crawford and Johnson, 1973).

Stewart Site

More than 100 acre-feet (123,300 m^3) of water was recharged into a 190-foot (58 m) well near Dawn, Texas. Playa-lake water that contained from 10 to more than 150 mg/l suspended sediment was recharged at an average rate of 600 gal/min (38 l/s). The well was rotary drilled and naturally developed. The casing was mill slotted from 50 feet (15 m) to 190 feet (58 m). Injection was by gravity flow under about 50 feet (15 m) of head and there was no substantial decrease in the permeability of the Ogallala aquifer during the test. Recharge was through secondary solution openings in a calcium carbonate-cemented medium and coarse sand. The tests were conducted by the U.S. Geological Survey.

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