# EVALUATION OF THE POTENTIAL FOR ARTIFICIAL GROUND-WATER RECHARGE IN EASTERN SAN JOAQUIN COUNTY, CALIFORNIA--PHASE 3

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## CONVERSION FACTORS

For readers who prefer to use metric (International System) units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

| Multiply inch-pound unit | By | To obtain metric unit |
|---|---|---|
| foot (ft) | 0.3048 | meter |
| foot per day (ft/d) | 0.3048 | meter per day |
| foot per year (ft/yr) | 0.3048 | meter per year |
| gallon per minute (gal/min) | 0.003785 | cubic meter per minute |
| inch | 25.40 | millimeter |
| mile (mi) | 1.609 | kilometer |
| square mile ($mi^2$) | 2.590 | square kilometer |

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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## ABSTRACT

Infiltration tests were used to evaluate the potential of basin spreading surface water as a means of artificially recharging the aquifer system in eastern San Joaquin County, California. Two infiltration sites near Lockeford and Linden were selected on the basis of information collected during the first two phases of the study.

Data from the infiltration tests indicate that the two sites are acceptable for recharge by the basin-spreading method. Infiltration rates ranged between 6.7 and 10.5 feet per day near Lockeford and between 2.6 and 11.2 feet per day near Linden. Interpretation of these data is limited by lack of information on the response of the saturated zone during testing and by the inherent difficulty in extrapolating the results of small-scale tests to larger long-term operations.

Lithology is a major factor that controls infiltration rates at the test sites. The unsaturated zone is characterized by heterogeneous layers of coarse- and fine-grained materials. Clay layers of low hydraulic conductivity commonly form discontinuous lenses that may cause a transient perched water table to develop during recharge. Water-level measurements from wells screened in the unsaturated zone indicate that the perched water table could reach the land surface after 2 and 5 months of recharge near Lockeford and Linden, respectively. These figures probably represent the minimum time necessary for saturation of the land. Another major factor that affects infiltration rates is the quality of the recharge water, particularly the suspended-sediment content. The clogging action of suspended sediment may be minimized by (1) pretreatment of recharge water in a settling pond, (2) adherence to a routine program of monitoring and maintenance, and (3) proper design of the recharge facility. Other factors that affect infiltration rates include basin excavation technique, basin shape, and maintenance procedures. Efficient operation of the recharge facility requires careful attention to the relation between subsurface water levels and infiltration rates.

## INTRODUCTION

Ground-water pumpage has lowered the water table in eastern San Joaquin County. Poor-quality ground water has moved from a degraded aquifer to the west into the Stockton area where water levels have declined below sea level (California Department Water Resources, 1967, fig. 1). Water levels generally have declined at an average rate of 1.7 ft/yr from 1947 to 1984, and saline ground water has moved inland about 1 mile between 1963 and 1983 (Brown and Caldwell, 1985). Projected increases in water demand may accelerate the degradation of the ground-water resource. In an effort to alleviate problems that result from declining water levels in San Joaquin County, the U.S. Geological Survey, in cooperation with the San Joaquin County Flood Control and Water Conservation District, began a three-phase study in the summer of 1980 to evaluate the potential for artificially recharging the aquifer system with surplus surface water that is available during the winter and spring months.

The study was carried out in three successive phases: classification of areas for recharge potential (phase 1), evaluation of favorably classified recharge areas by test drilling and selection of percolation-pond test sites (phase 2), and determination of potential infiltration rates from percolation-pond tests (phase 3).

During phase 1 of the study, information on geology, soils, driller's logs, and land use was used to develop a series of maps that define favorable areas for ground-water recharge. Hydraulic conductivities were estimated for geologic units and soils. Areas of hardpan and claypan were delineated. Specific yields, estimated from driller's logs, were used to define areas with deep sediments receptive to recharge. This series of maps was used collectively to determine areas of favorable potential for the basin-spreading recharge method. Finally, data on land use were used to define areas suitable for location of recharge facilities. Results of phase 1 are summarized by Mitten (1982).

On the basis of the previous work, 11 test holes were drilled to, or below, the water table in three selected areas during phase 2. Lithologic and geophysical logs from these test holes were used to define the characteristics of the sediments above the water table and to evaluate the recharge potential of the aquifer system. On the basis of this information, the local area at each test-hole site was rated poor, fair, or good for the purpose of artificial recharge. Results of phase 2 are summarized by Ireland (1983).

This report summarizes the data collected during phase 3 and evaluates the suitability of the areas for artificial recharge. On the basis of conclusions from the the first two phases, infiltration test sites were selected near the towns of Lockeford and Linden (fig. 1). Infiltration-rate and ground-water-level data collected at these sites were used to assess the feasibility of artificially recharging the aquifer.

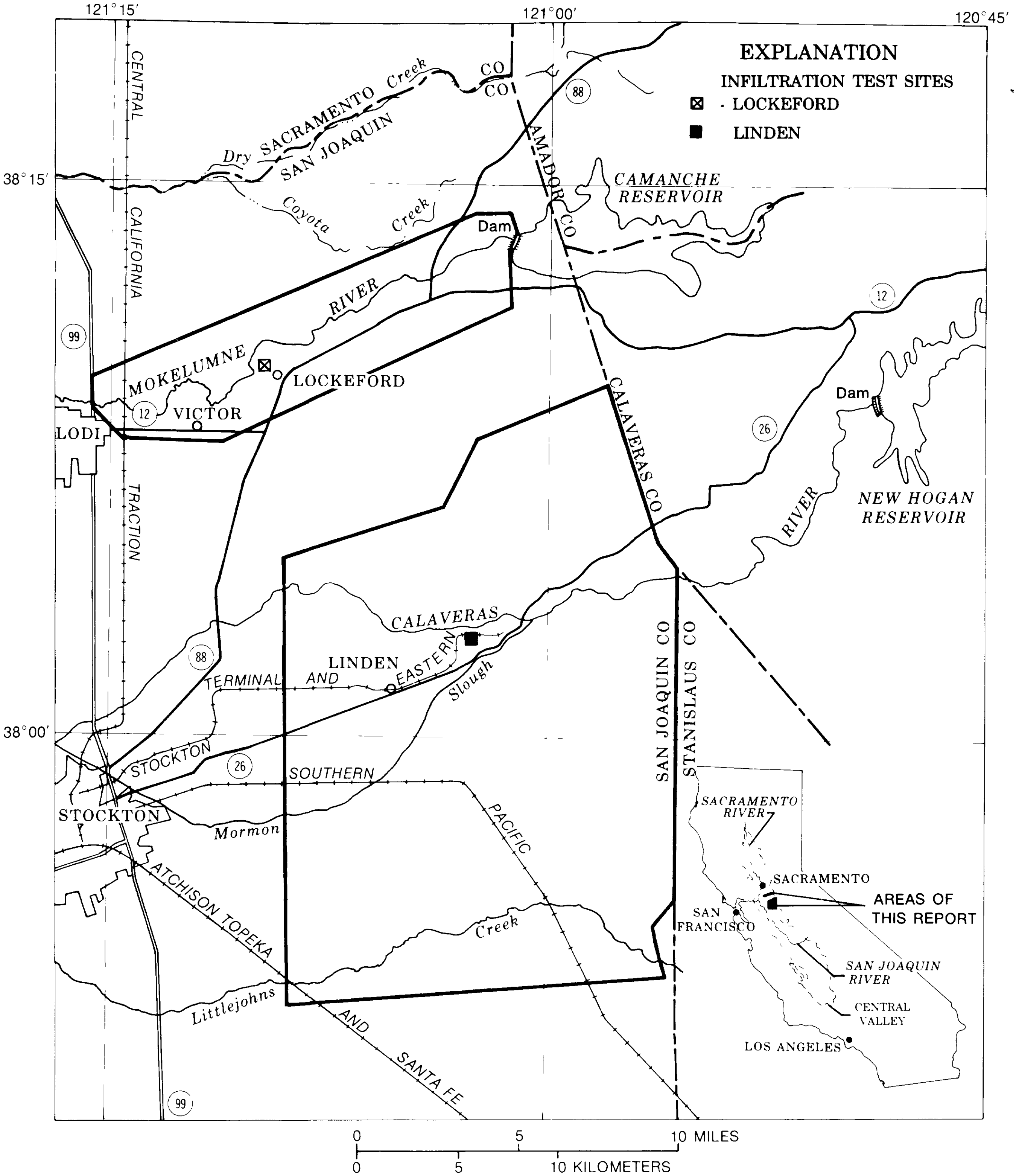


**FIGURE 1. — Location of study area.**

The test facilities at the two sites consisted of a supply well, percolation pond, and a network of observation wells. Inflow rates and water levels were monitored in the ponds to determine infiltration rates. Water-level rise in the unsaturated zone was monitored in observation wells at the sites during infiltration testing.

Collection of data for this study was made possible by the cooperation of many landowners and public agencies. Mr. Tom Iwamiya and others of the San Joaquin County Flood Control and Water Conservation District were responsible for site acquisition, construction of the infiltration-test facilities, and gathering of data. Mr. Lee Hall and others of the San Joaquin County Local Health District also were helpful and cooperative. Special thanks are given to Mr. Randy Lipelt, whose property was used during the Lockeford infiltration test, and to Mr. John Boggiano, whose property was used during the Linden infiltration test.

## DESCRIPTION OF STUDY AREA

The study area encompasses about 250 mi$^2$ in east-central part of California's Central Valley, east of the confluence of the San Joaquin and Sacramento Rivers and west of the Sierra Nevada. The study area consists of two parts: the northern part (about 50 mi$^2$) along the Mokelumne River and the southern part (about 200 mi$^2$) along the Calaveras River, Mormon Slough, and Littlejohns Creek. Topography in the area is characterized by low hills in the east (the western edge of the Sierra Nevada foothills), a gently rolling terrain in the central part, and a nearly level valley floor in the west (Mitten, 1982).

### Geology

Unconsolidated materials in the study area are stream-deposited, lenticular beds of gravel, sand, silt, and clay that are continuous for only a few tens of feet. Logs from observation wells drilled near the two recharge sites confirm the heterogeneous nature of the upper unconsolidated deposits (Ireland, 1983). Stream-channel deposits consisting of sand and gravel with lesser amounts of silt and clay underlie the area near Lockeford. Alternating lenses of sand and silt compose the upper 20 to 40 feet of sediments. A gravel layer is present at the base of the finer grained sediments.

The area near Linden is underlain by discontinuous lenses of gravel, sand, silt, and clay. Well logs from the Linden site show a similar lithology to the Lockeford site. Fine-grained materials compose the upper 15 to 25 feet of sediments and overlie a basal gravel bed.

## Hydrology

Depth to the water table in the study area ranges from a minimum of about 50 feet near Victor to at least 140 feet in the southwestern part of the area (Mitten, 1982). Based on a water-level contour map prepared by the San Joaquin County Flood Control and Water Conservation District (Iwamiya, 1985), depths to the water table near Lockeford and Linden are about 90 and 115 feet below land surface. Perched water probably occurs at shallower depths in the intervening sedimentary beds within the unsaturated zone, which are gradational and occur as lenses. Lenses of low permeability materials may restrict vertical percolation of recharged water and cause localized perching of water. Ground-water flow in the unsaturated zone may alternate primarily between the vertical and horizontal directions in response to variations in hydraulic conductivity of the sediments.

The hydraulic conductivity, specific yield, and distribution of unconsolidated deposits control the migration and limit the quantity of water recharged to the aquifer system. Infiltration rates are initially constrained by the character and composition of soil at the recharge site. For example, under saturated conditions a clay layer may form a hydraulic barrier, hindering the downward percolation of recharge water. Test holes drilled near the recharge sites intercepted lenticular clay beds, many of them silty, but no hardpan or claypan that would slow or prevent percolation (Ireland, 1983).

The hydraulic head in a ground-water body is equal to the elevation of the free water surface with respect to a reference datum, such as sea level. It is equivalent to water levels measured in wells tapping the aquifer of interest. The ground-water gradient generally follows topography. The difference in hydraulic head in a hydraulically continuous aquifer governs ground-water flow. The resultant hydraulic gradient in the ground-water system is from areas of high head (or water level) to those of low head. The ground-water gradient in the study area is affected by variations in recharge, discharge (pumpage), and hydraulic characteristics of subsurface layers. Water levels for the spring of 1985 (Iwamiya, 1985) show that ground water generally moved toward an area of depressed water levels south of Linden and Stockton (fig. 2). The local ground-water gradient near the Lockeford site is generally to the south and away from the Mokelumne River. The local gradient near the Linden site is generally also to the southwest and away from the Calaveras River. In both areas, recharge from the rivers produces a ridge in the ground-water table and results in the observed local gradients.

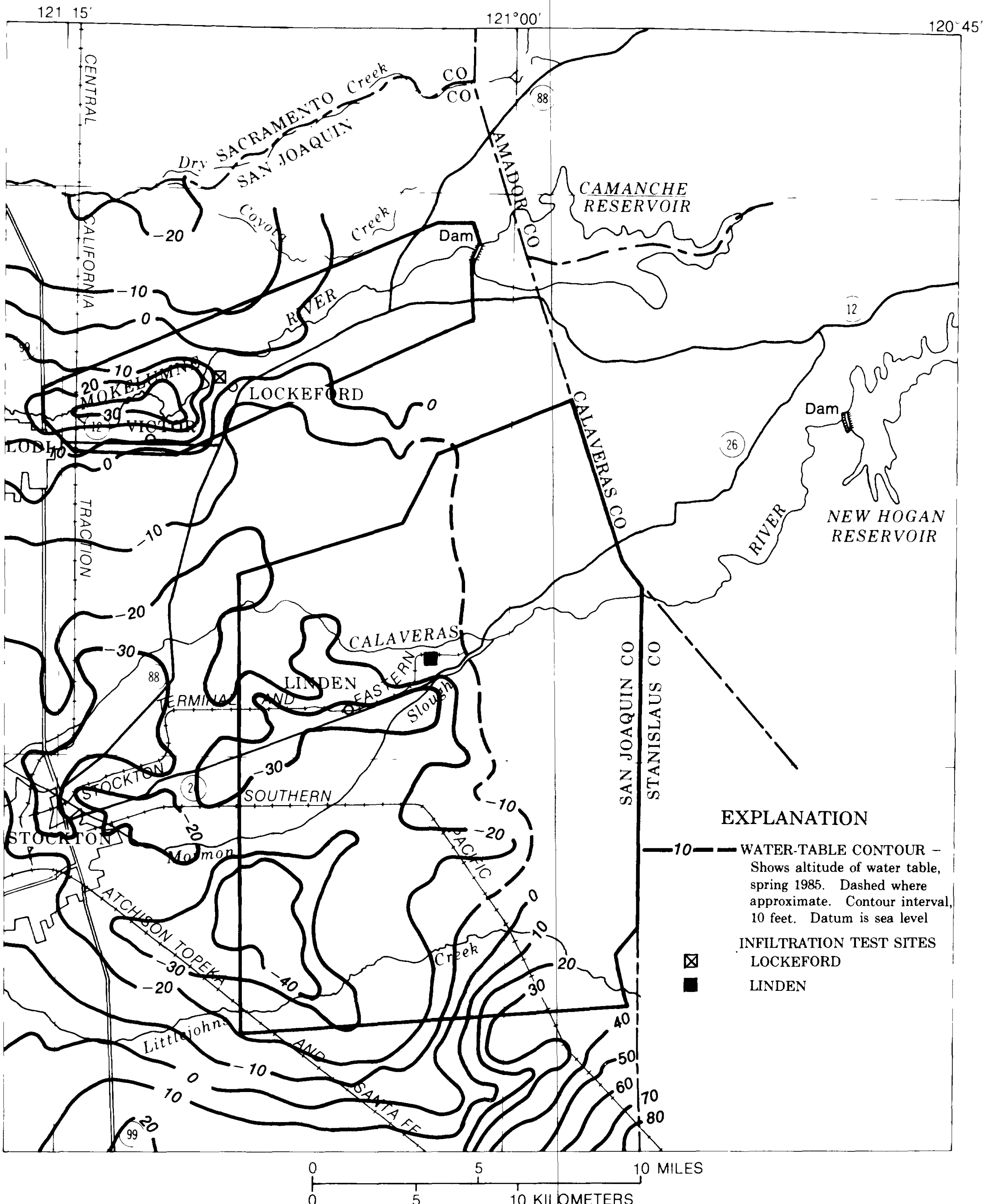


**FIGURE 2. – Water-table contours, spring 1985 (from Iwamiya, 1985).**

## ARTIFICIAL RECHARGE

### Concept

Any process by which man fosters the transfer of surface water into the ground-water system can be classified as artificial recharge (Freeze and Cherry, 1979). Ground-water basins may be recharged artificially in order to increase the natural supply of ground water and (or) to alleviate water-quality problems. A variety of recharge methods have been developed, including water spreading, recharging through pits and wells, and pumping to induce recharge from surface-water bodies.

According to Todd (1980), artificial recharge projects are designed to serve one or more of the following purposes:

(1) Maintain or augment the natural ground water as an economic resource.
(2) Coordinate operation of surface- and ground-water reservoirs.
(3) Combat adverse conditions such as progressive lowering of ground-water levels, unfavorable salt balance, and saline-water intrusion.
(4) Provide subsurface storage for local and imported surface water.
(5) Reduce or stop significant land subsidence.
(6) Provide a localized subsurface distribution system for established wells.
(7) Provide treatment and storage for reclaimed wastewater for subsequent reuse.
(8) Conserve or extract energy in the form of hot or cold water.

Thus, in most situations, artificial recharge projects serve not only as water-conservation mechanisms, but also assist in overcoming problems associated with overdrafts.

### Basin-Spreading Method

Spreading basins permit temporary storage of large surface-water flows that may exceed the infiltration capacity of channels and canals in an area (Davis and others, 1964). According to Hillel (1982), infiltration is the process of water entry into the soil, generally by downward flow, and is defined as the volume flux of water flowing into the profile per unit of soil surface area. The recharge process may cause the growth of a ground-water mound beneath the basin. The extent of the mound and its rate of growth depend on the size and shape of the percolation basin, the duration and rate of recharge, the configuration of subsurface lithologic layers, and the hydraulic characteristics of the layers. Spreading basins are generally constructed to facilitate infiltration of recharge water and to minimize the potential saturation of the land surface from recharge-mound growth.

Scalmanini and Scott (1979) and Nightingale and Bianchi (1981) have described factors to be considered in the construction of a recharge basin. Size and geometry of basins are adjusted to obtain the desired recharge rate.

## Factors Affecting Infiltration Rates

The potential for artificial recharge by basin spreading is determined largely by aquifer conditions at or near the recharge site if the storage capacity of the aquifer is considered to be infinite. Under most conditions, infiltration rate at the soil surface is the governing factor. In some areas, subsurface layers with low aquifer hydraulic conductivity, rather than soils, can govern the long-term infiltration rate.

Recharge rates in spreading basins are usually determined by the infiltration rate at the soil-water interface. Initial declines in infiltration rates usually result from a reduction in the matric suction gradient (Hillel, 1982). This reduction occurs as the wetting zone moves downward and gravity flow begins to dominate the infiltration process. Clogging at the surface of the spreading basin also can be a factor in reduced infiltration rate. The change in infiltration rate with time generally follows a sigmoid-shaped curve (Scalmanini and Scott, 1979). This phenomenon is shown in figure 3. Three distinct segments may be noted on the curve. The first period is characterized by a decreasing infiltration rate and is attributed to swelling, settling, and dispersion of the soil matrix due to the application of water. During the second period, the infiltration rate increases, probably in response to an increase in hydraulic conductivity as entrapped air is expelled or removed by dissolution. The first two periods represent physical changes in the soil matrix during a short period, usually less than 2 months. The infiltration rate decreases exponentially during the third and final period, affected primarily by biological activity and deposition of suspended solids.

A variety of physical, chemical, and biological factors affect basin-recharge rates. These factors interact in varying degrees to either decrease or increase the infiltration rate and include the following:

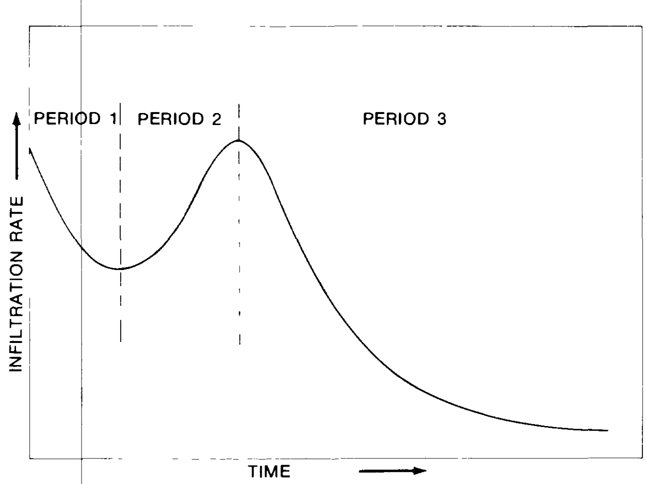


**FIGURE 3. — General behavior of infiltration rate during recharge (after Scalmanini and Scott, 1979).**

Filtration Clogging--A common cause of a reduction in infiltration rates is filter-packing of water borne sediment and (or) the formation of a layer of fine-grained, low-permeability material over the soil surface. Suspended sediment in recharge water and silt derived from bank erosion and wind action settle to the bottom of the recharge basin and may move into the soil matrix, plugging pore spaces.

Biological Clogging--Bacterial growth within the soil matrix and (or) algal growth on the soil surface also may reduce infiltration rates.

Chemical Reactions--The interaction between recharge water, subsurface water, and soil may result in precipitation, dissolution, and ion-exchange reactions. Precipitation and dissolution reactions will act to reduce and increase soil hydraulic conductivity, respectively. Exchange of sodium for calcium on expandable clays may produce swelling and (or) dispersion which will reduce the hydraulic conductivity of the soil (McNeal and others, 1966).

Soil Compaction--Compaction of soil materials may occur during saturation causing a significant reduction in hydraulic conductivity. Land subsidence resulting from saturation may be evaluated by monitoring changes in ground-surface elevation in the pilot basin.

Air Entrapment--Air trapped in the soil beneath the recharge basins may act as a barrier to downward moving recharge water and result in accumulation of water in transient perched water.

Hydraulic Effects--Confining materials, such as clay lenses, or trapped atmospheric gases result in transient perched water and formation of a recharge mound because of low aquifer storage capacity or transmissivity (Scalmanini and Scott, 1979). The formation of perched water on clay layers is illustrated in figure 4, a generalized section showing soil type and relative saturation with depth. Intersection of the perched water with the recharge surface results in reduced recharge rates. The figure depicts the case where percolating recharge water has saturated the sand layer beneath the basin. Intersection of the perched water with the recharge surface results in reduced recharge rates. As the distance through the soil to the edge of the mound increases, the driving force necessary to produce recharge becomes greater and the rate of recharge is diminished. Water that has passed through the restrictive upper clay layer has formed a perched water table in the lower sand layer, which rests on the lower clay layer of figure 4. Recharge water that penetrates the lower clay layer flows downward through the unsaturated part of the sand and gravel layer, eventually reaching the ground-water body.

Seaburn (1970) found that the depth of water in the pond and the infiltration rate were not directly related for a percolation pond on Long Island, New York. Seaburn attributed variations in infiltration rates chiefly to antecedent soil mixture conditions, water temperature, barometric pressure, and differences in the hydraulic conductivity of soil materials. Viscosity of recharge water, a function of temperature, also can affect infiltration rates. Infiltration rates are lowered with increasing viscosity (lower temperature) by the increasing difficulty of fluid entry into the pores at the infiltration surface (Scalmanini and Scott, 1979).

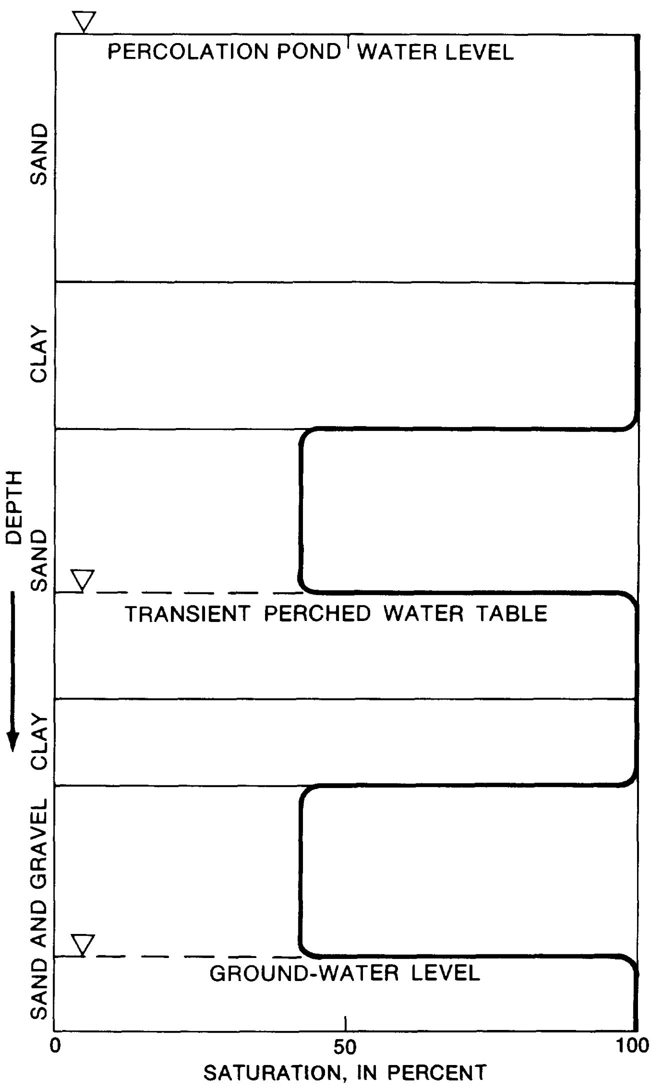


**FIGURE 4. — Soil type and relative saturation with depth.**

## INFILTRATION TESTS

### Methods

The test facilities near Lockeford and Linden each consist of a supply well, a percolation basin, and a network of observation wells (fig. 5). The Lockeford site also included a storage basin for recharge water. However, the storage basin was abandoned during the test because it leaked and affected water levels in the observation wells. Table 1 is a listing of construction data for observation wells at both sites. The wells were completed within the upper 40 feet of the soil column and were used to monitor water-level rise in shallow subsurface materials during recharge. Because the wells were not grouted, they might have been conduits for percolation of recharge water.

The percolation basins at the Lockeford and Linden sites were 5 feet deep with bottom dimensions of 25 by 100 and 25 by 40 feet. Heavy construction equipment was restricted from the bottom of the basins to prevent soil compaction during excavation. To improve its infiltration capacity, the soil was ripped to a depth of 4 feet. The side slopes in the finished basins were approximately 2 to 1. The general features of the basins are shown in figure 5.

Recharge water was admitted through a pipe at the bottom of the basins to minimize erosion of the sides. Inflow rate and water depth were monitored and the infiltration rate was determined by calculating the volume of water in cubic feet, passing through the area of the basin in square feet per unit of time (day). Units for infiltration rate (volume per area per day) reduce to feet per day. Subsequent impact on the aquifer system was assessed from water-level data collected at the observation wells. However, none of the observation wells extended down to the depth of the regional aquifer being recharged.

TABLE 1.-- Well-construction data

[All wells are constructed with 2-inch diameter PVC casing. Observation well: S, shallow; D, deep. Location of wells shown in fig. 5. Casing depth and perforated interval are given, in feet, below land-surface datum]

| Observation well | Casing depth (ft) | Perforated interval (ft) |
|---|---|---|
| Lockeford | | |
| 1S | 27 | 22-27 |
| [1]1D | 37.5 | 27.5-37.5 |
| 2S | 21 | 16-21 |
| 3S | 19 | 9-19 |
| 3D | 41 | 36-41 |
| 4S | 19 | 0-19 |
| 4D | 28 | 23-28 |
| Linden | | |
| 1S | 20 | 10-20 |
| 1D | 31 | 21-31 |
| [1]2S | 19.5 | 10-19.5 |
| 2D | 27 | 20-27 |
| [1]3S | 20 | 10-20 |
| 3D | 28.5 | 20.5-28.5 |
| [1]4S | 20 | 10-20 |
| 4D | 27 | 20-27 |

[1]Well was dry during testing.

### Results

A minimum infiltration rate of 0.5 ft/d is generally considered essential to most recharge operations (Lichtler and others, 1980). Initial infiltration rates at the two test ponds exceeded 0.5 ft/d. Infiltration rates ranged between 6.7 and 10.5 ft/d at the Lockeford site and between 2.6 and 11.2 ft/d at the Linden site (table 2). The test data indicate a positive correlation between the water-level head in the pond and the infiltration rate. Increased inflow rate and consequent higher head in the basin resulted in a greater infiltration rate.

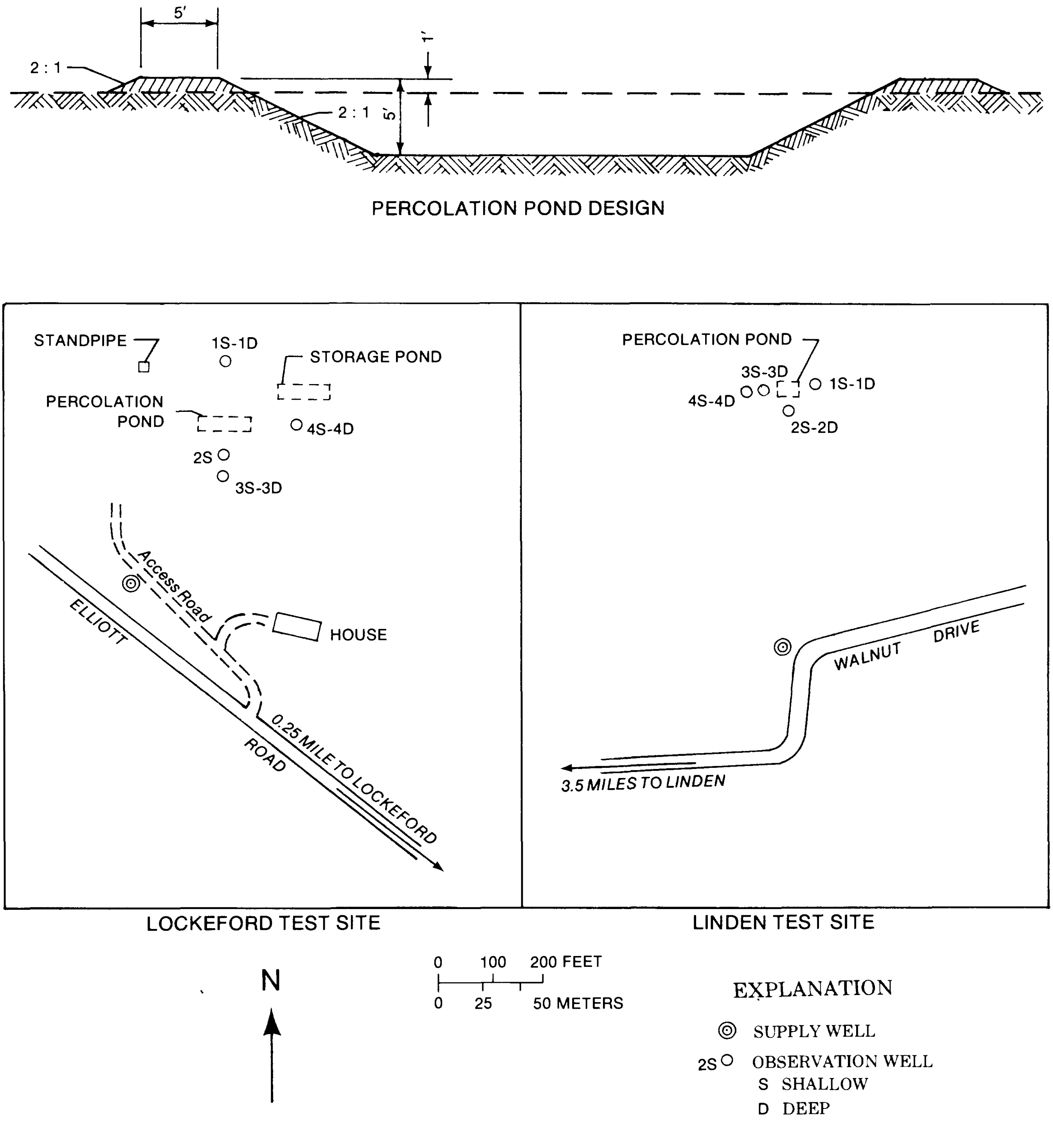


**FIGURE 5. — Infiltration test sites near Lockeford and Linden.**

TABLE 2.-- Infiltration-test data, 1984

[Abbreviations: gal/min, gallons per minute; ft, feet; ft/d, feet per day]

| Date | Inflow rate (gal/min) | Water depth in percolation pond (ft) | Infiltration rate (ft/d) |
|---|---|---|---|
| | Lockeford | | |
| Jan. 6-10 | 25 | 0.1 | 8.0 |
| Jan. 10 | 0 | decline | [1]6.7 |
| Jan. 10-20 | 150 | 0.7 | 10.5 |
| Jan. 20 | 0 | decline | [1]9.0 |
| | Linden | | |
| Nov. 26-Dec. 4 | 25-38 | 2-3 | 11.2 |
| Dec. 5-12 | 5-12 | 0.4-1.0 | 2.6 |
| Dec. 14-28 | 28-42 | 0.3-3.6 | 11.2 |

[1]Infiltration rate calculated from rate of water-level decline following termination of inflow to the percolation basin.

The most critical factor affecting long-term infiltration rates at the two sites is probably the hydraulic conductivity of the soil and alluvial materials between the surface and the aquifer. This material must be sufficiently permeable to allow significant quantities of water to percolate to the water table. The change in water levels in the observation wells, inflow rates, and pond water levels in the observation wells at the Lockeford and Linden test sites are shown in figures 6 and 7, respectively. Water-level data from both sites indicate perching of recharge water and retardation of downward flow. The greater initial response in water level to recharge at the Lockeford site results from the combined effects of recharge from the storage and recharge ponds. The rate of water-level rise declined dramatically on January 10, 1984, when inflow to the storage pond was shutdown. Similarly, at Linden the decline in water levels from December 4-14, 1984, (fig. 7) resulted from a reduction in the flow rate to the basin. Water levels at both sites may be grouped into a shallow and deep zone. This zonation probably results from perching of water on discontinuous layers of low permeability. At the Linden site, three of the shallow wells were not affected by perched water and remained dry. The hydrograph at the Lockeford site shows a larger rise in water level than at the Linden site corresponding to greater inflow volume.

Projected water-level rises at the Lockeford and Linden sites indicate that perched water would intersect the land surface after 2 and 5 months, respectively. These figures probably represent the minimum time for saturation of the land since horizontal flow (drainage) would increase with head. Diminished recharge, a result of the natural decay in infiltration rate (from clogging and hydraulic effects), would also slow the development of the perched water. Similarly, water-level rises would be attenuated by seasonal decline in recharge rates and during maintenance operations.

## Limitations

Interpretation of the infiltration data collected near Lockeford and Linden is restricted by the scope and nature of the infiltration tests. The test facilities comprise a small area and infiltration tests were completed during a short period of time. Data collected during these tests may not be accurately extrapolated to define infiltration rates for larger areas over longer periods of time. Additionally, variations in water-quality conditions between infiltration-test facilities and permanent recharge basins may produce dissimilar results. However, the infiltration rates determined do indicate the generally favorable potential for recharge in the areas classified during the previous phases of this study.

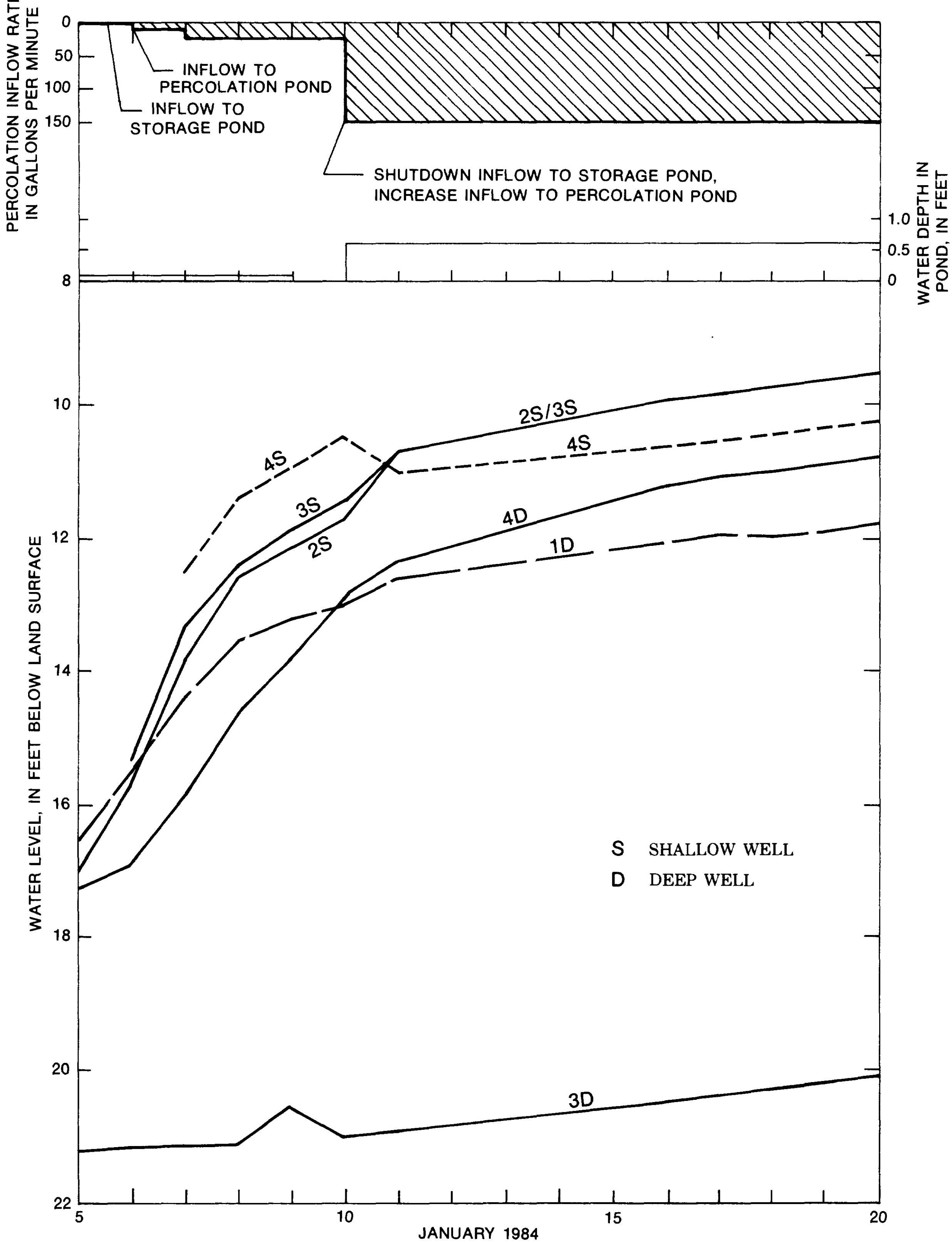


FIGURE 6. — Water-level change in observation wells and pond at Lockeford test site and inflow rates during January 1984 (Location of wells shown in fig. 5).

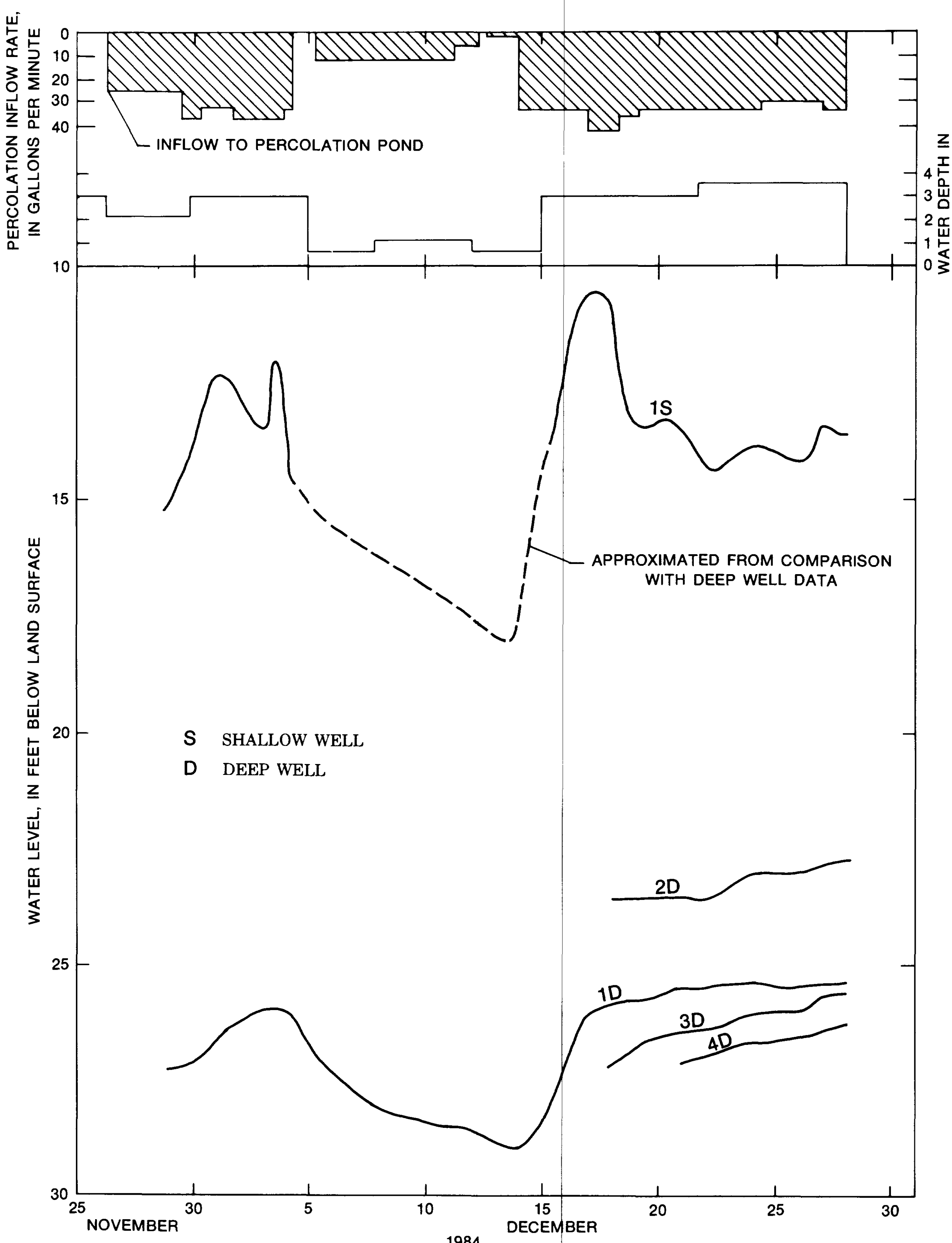


**FIGURE 7.** — Water-level change in observation wells and pond at Linden test site and inflow rates during November and December 1984. (Location of wells shown in fig. 5.)

The small area of the recharge test facilities may not adequately represent average, large-scale variations in lithology, and consequently, average soil hydraulic conductivity in the Lockeford and Linden areas. Lateral and vertical variation in hydraulic conductivity results from a heterogeneous aquifer system composed of lenticular beds of fine and coarse materials. The results of small-scale infiltration tests may be biased by the presence of above- or below-average amounts of fine- or coarse-grained materials. Similarly, short-term tests may not accurately predict long-term infiltration rates. The shape of the test pond basin also affects infiltration rates and may not accurately represent hydraulic characteristics of the final percolation pond design. In addition to these constraints, the effects of recharge on the lower, saturated ground-water zone were not monitored to determine water movement.

The hydraulic conductivity of soil materials may be affected by the quality of applied recharge water. Recharge water may cause chemical reactions in the soil matrix that increase or decrease hydraulic conductivity. Suspended sediment in recharge water will eventually clog soil pore spaces and reduce hydraulic conductivity. The quality of ground water used at the infiltration test sites may differ substantially from that of the surface water intended for full scale recharge facilities. As a consequence, infiltration rates may vary in response to changes in water quality.

## OPTIMIZATION OF RECHARGE

Optimal construction and operation of recharge facilities depends on a knowledge of the local lithology and an effective construction, monitoring, and management program. An efficient basin is excavated as to avoid soil erosion and compaction; a sump, or a tiered bottom, will facilitate cleaning and maintenance. To minimize levee erosion due to wave action, the basin width would be limited to 560 feet in the direction of the prevailing strongest winds to reduce wave height (Nightingale and Bianchi, 1981). Soil material for the levees would be excavated from a central borrow pit. Side slopes greater than 45 degrees ensure cleaning of sedimentary material. Flatter slopes promote growth of vegetation and, subsequently, result in increased burrowing animal and mosquito populations. However, grass filters may help prevent sedimentation at the soil surface and the grass roots may increase permeability at the soil surface.

Use of soil conditioners also may reduce slaking and clogging. Cleaning and other maintenance activities intended to restore infiltration rates may actually compact the soil surface and eventually create an impervious pan just below the depth of treatment. To avoid compaction of the basin floor, the pond needs to be allowed to dry completely before cleaning and removing deposited sediment. Basin shape will have a strong effect on the infiltration rate (Scalmanini and Scott, 1979). Because the sides of the basin contribute to the total volume of recharge, the perimeter-to-area ratio is maximized. Rectangular basins are superior to square and circular basins of the same areal extent. The greater water column in deep ponds reduces the penetration of sunlight and inhibits algal growth (and clogging) at the pond bottom. Such ponds, as a result of larger wetted areas, possess high recharge capacities and allow long periods of operation. However, anaerobic bacteria may cause clogging in deep ponds with little circulation.

Efficient use of wet-dry cycle timing will allow maintenance of the recharge basin, reduce buildup of the recharge mound, and minimize biological clogging. Conjunctive use of the stream channel may be made in the summer months by constructing dikes to capture more recharge flow to the ground-water system. Because turbulence within a basin can lower the infiltration rate, energy-dissipating structures are generally used to prevent scour at the inlet and reduce sealing of the basin floor with scoured materials that will settle out of suspension.

Installation of clusters of observation wells screened at regular depth intervals down to the saturated zone would provide lithologic information and facilitate monitoring for the effects of recharge. Water levels in the wells and basin, water quality of surface and ground water, and inflow rates to the basin need to be monitored during recharge. Periodic measurement of silt depth would determine the basin cleaning schedule and would permit correlation with decline in infiltration rates. Efficient operation of the recharge facility relies on careful attention to the relation between subsurface water levels and infiltration rates.

## CONCLUSIONS

The Lockeford and Linden infiltration test data indicate that both sites would be acceptable for artificial recharge. Infiltration rates ranged between 6.7 and 10.5 feet per day near Lockeford and between 2.6 and 11.2 feet per day near Linden. The hydraulic conductivity and distribution of shallow subsurface soil layers may limit infiltration rates. Water-level measurements from wells screened in the unsaturated zone indicate that the perched water table could reach the land surface after 2 and 5 months of recharge near Lockeford and Linden, respectively. To reduce the development of the perched water and prevent saturation of the land, inflow rates and wet-dry cycles may be adjusted accordingly. Pretreatment of recharge water in a settling basin may reduce maintenance and clogging in the percolation pond. The clogging action of suspended sediment may be minimized by (1) pretreatment of recharge water in a settling pond, (2) adherence to a routine program of monitoring and maintenance, and (3) proper design of the recharge facility. In general, the quality of recharge and ground water may be monitored .to predict potential adverse chemical reactions and to describe the movement of recharge water.

## REFERENCES CITED


California Department of Water Resources, 1967, San Joaquin Valley ground-water investigations: California Department of Water Resources Bulletin 146, 177 p.

Brown and Caldwell, Consulting Engineers, 1985, Eastern San Joaquin County ground water study: Final report, 129 p.

Davis, G.H., Lofgren, B.E., and Seymour, Mack, 1964, Use of ground-water reservoirs for storage of surface water in the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 1618, 125 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Hillel, Daniel, 1982, Introduction to soil physics: New York, Academic Press, (Harcourt Brace Jovanovich, Publishers), p. 211-231.

Ireland, R.L., 1983, Evaluation of the potential for artificial ground-water recharge in eastern San Joaquin County, California--Phase 2: U.S. Geological Survey Open-File Report 83-4207, 28 p.

Iwamiya, T.M., 1985, Semiannual ground water report, spring 1985: San Joaquin County Flood Control and Water Conservation District, 12 p.

Lichtler, W.F., Stannard, D.I., and Kuoma, Edwin, 1980, Investigations of artificial recharge of aquifers in Nebraska: U.S. Geological Survey Water-Resources Investigations Report 80-93, 112 p.

McNeal, B.L., Norrell, W.A., and Coleman, N.T., 1966, Effect of solution composition on the swelling of extracted soil clays: Soil Science Society of America, Proceedings, v. 30, p. 313-317.

Mitten, H.T., 1982, Preliminary evaluation of the potential for artificial recharge in eastern San Joaquin County, California: U.S. Geological Survey Open-File Report 82-123, 40 p.

Nightingale, H.I., and Bianchi, W.C., 1981, Artificial basin recharge: Water-Engineering and Management, Volume Reference HB, p. R85-R87, R89-R92.

Scalmanini, J.C., and Scott, V.H., 1979, Design and operation criteria for artificial ground-water recharge facilities: Water Science and Engineering Paper No. 2009, 93 p.

Seaburn, G.E., 1970, Preliminary results of hydrologic studies at two recharge basins on Long Island, New York: U.S. Geological Survey Professional Paper 627-C, 17 p.

Todd, D.K., 1980, Ground-water hydrology: New York, John Wiley, 535 p.


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