PROJECT COMPLETION REPORT

Development of Systems for Ground Water Recharge Into the Ogallala Formation

FILE COPY

by
Marvin J. Dvoracek
Sam H. Peterson

OWRR Project No. B-041-TEX
Matching Grant Agreement
No. 14-01-0001-1949

January 1969-June 1971

Texas
Tech
University

WATER
RESOURCES
CENTER

Lubbock, Texas

WRC-71-4
June 1971

DEVELOPMENT OF SYSTEMS FOR GROUND WATER RECHARGE INTO THE OGALLALA FORMATION

A

RESEARCH PROJECT TECHNICAL

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JUNE 1971

The work upon which this report is based was supported in part by funds provided by the United States Department of Interior, Office of Water Resources Research, as authorized under the Water Resources Act of 1964.

A LIST OF PUBLICATIONS AND REPORTS RESULTING

FROM THIS PROJECT

Dennis, S. A., M. J. Dvoracek, and S. H. Peterson. 1970. Artificial Recharge of Hydrologically Isolated Aquifers. Paper for presentation at Irrigation and Drainage Specialty Conference, November 4-6, 1970, American Society of Agricultural Engineers and American Society of Civil Engineers, Miami Beach, Florida.

Dennis, S. A., M. J. Dvoracek, and S. H. Peterson. 1970. Artificial Recharge of Hydrologically Isolated Aquifers. Paper for presentation at Winter Meeting American Society of Agricultural Engineers, December 8-11, 1970, Chicago, Illinois.

Dvoracek, M. J. and S. H. Peterson. 1969. Development of Systems for Ground Water Recharge into the Ogallala Formation. In Water Resources Institute 1969 Annual Report. Texas A & M University, College Station, Texas.

Dvoracek, M. J. and S. H. Peterson. 1969. Development of Systems for Ground Water Recharge into the Ogallala Formation. In Progress Reports on Research, College of Agricultural Sciences, Texas Tech University, Lubbock, Texas.

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runoff waters, which collect in the numerous playa lakes located in this region, for artificial ground water recharge operations offer enormous potential to manage and conserve both rainfall and ground water resources. At the present time only a small percentage of this water is put to beneficial use with most being wasted to evaporation.

The high sediment load carried by these runoff waters does complicate recharge operations, however the successful elimination of this restriction and the development of an effective means of recharge will allow the utilization of the tremendous storage potential of the Ogallala Formation. In the future artificial ground water recharge may become an even more important factor in the storage of any waters which would be imported to the High Plains area.

REVIEW OF LITERATURE

Research studies in the United States in the field of artificial ground water recharge can be traced back to the 1880's when surface spreading was attempted at Denver, Colorado (2). Since this early attempt several additional methods have been developed such as: wells, pits, trenches, and shafts.

The first reported attempts to recharge the Ogallala Formation on the Southern High Plains of Texas occurred in

1918. These early attempts were primarily aimed at draining the playa lakes permitting use of the fertile soil in the lake bottoms for crop production with little thought to aquifer replenishment (4). The steady increase in ground water withdrawals starting in the mid-1940's, the rapidly accelerating decline of the water table, and the drought in the 1950's stimulated action in artificial recharge efforts on the Southern High Plains of Texas.

Ogallala water was used in the McDonald well field near Amarillo to observe the possibility of storing water in the Ogallala. Moulder and Frazor (8) reported in this study that problems in plugging or decreasing rate of recharge did not exist with the recharge of Ogallala water, which was relatively free of suspended particles.

Broadhurst (1) experienced plugging or silting in a gravity-flow recharge well, but by recharging 23 hours and pumping one hour maintained a higher average rate of recharge, 920 gallons per minute. During a 23 hour recharge period using a gravity-flow well at the High Plains Research Foundation (Halfway, Texas), Valliant (17) reported that 73 per cent of the solids were removed by surging the well every fifteen minutes. Conversely, Clyma (3) reported that 89 to 93 per cent of the sediment that entered the well during 24 hours of recharge remained in the well after a one hour pumping cycle.

Schwiesow (13), Dvoracek and Wheaton (5) were moderately successful with a gravity-flow recharge well using a filter system for removal of the suspended material before recharging. A clarification system was initiated by Hauser and Lotspeich (6) to add and mix flocculants to water prior to well recharge thus removing 90 per cent of the suspended solids from the turbid waters.

Johnson and Crawford (7) have been successful in using runoff waters and pressure injection into the Ogallala Formation. Rates up to 2,000 gallons per minute were obtained using an injection pressure between 50 and 80 psi. There appears to have been no plugging or silting of the well.

Dvoracek and Wheaton (5) studied pit recharge using turbid surface runoff water. Using pits with dimensions 250 feet by 100 feet by 10 feet deep, average recharge rates up to 1.5 feet per day were experienced during the five day period when the depth of water was above two feet. Rates declined when the water depth was below two feet or when additional sediment was deposited. With annual maintenance of these pits, declines in rate were not severe. Signor and Hauser (14) investigated pit recharge at Bushland, Texas. Using shallow pits extending into a sand layer rates ranging between 1.3 and 0.06 inches per hour were reported using clean water.

The use of shafts for artificial recharge into the Ogallala Formation was reported by Skodje (16), and Signor, Hauser, and Jones (15). Three shafts, 30 to 36 inches in diameter, were dug to a depth of 96 feet extending into sand at Bushland, Texas. A recharge rate up to 788 gpm of clean water was obtained in one of the shafts that had been modified by hydraulically mining a cavity in the sands of the dewatered Ogallala (15).

The problems encountered in studies using water carrying substantial sediment load has prompted the investigation of methods of clarifying or filtering runoff waters to be used in artificial recharge. Both mechanical filtration, (6,10, 11,12) and chemical filtration, (6,9) have been studied. Most processes used in these studies have had relatively high costs associated with them. This fact has motivated the search for improved filtration methods or recharge mechanisms not adversely effected by sediment.

EXPERIMENTAL PROCEDURE

The reported recharge studies were conducted on lands owned by Texas Tech University within the Northwestern city limits of Lubbock, Texas. This location contains a playa lake which was modified and is surrounded by land possessing several recharge facilities and mechanisms. Figure 1 illustrates the relative position of these and other features of the recharge area.

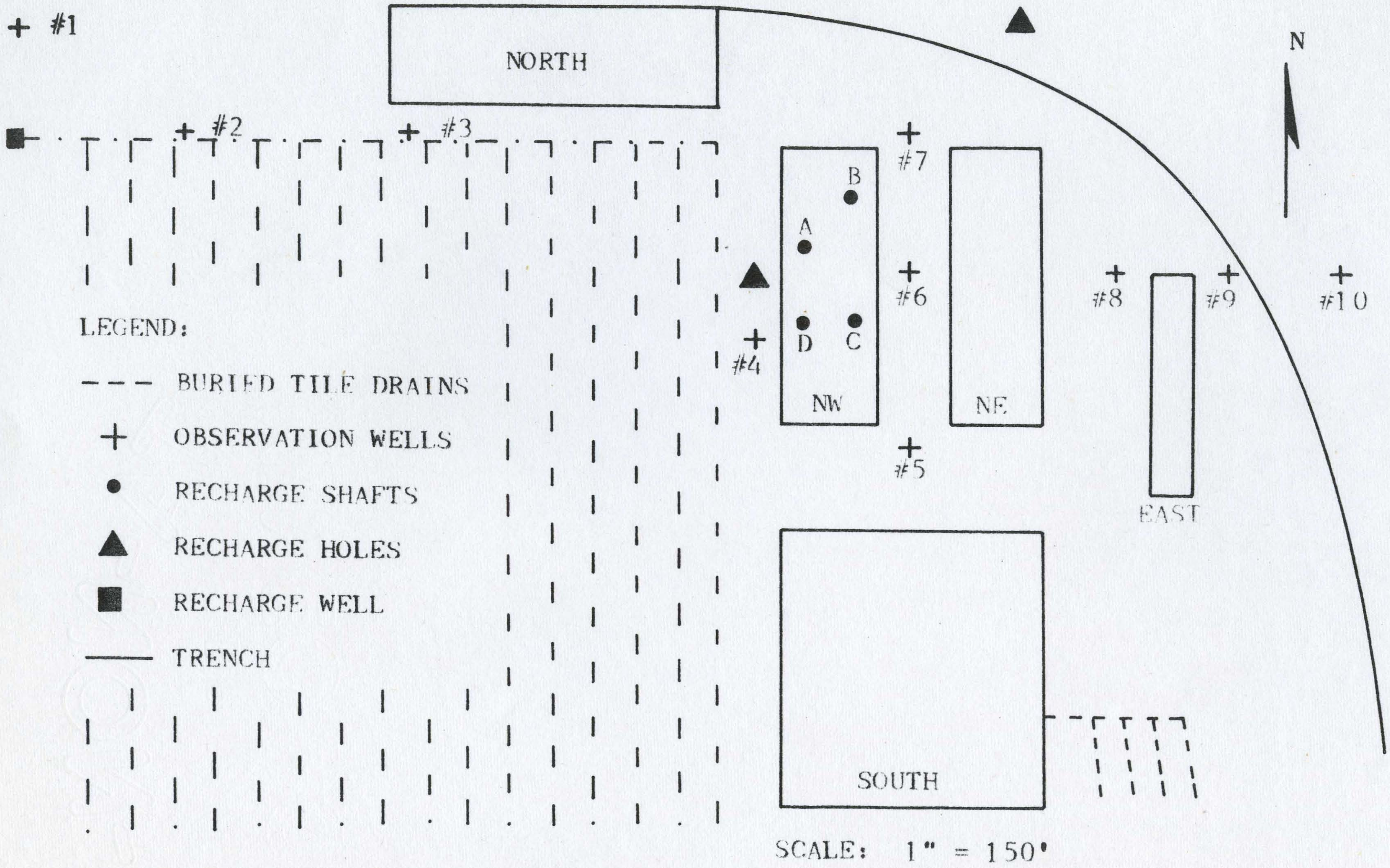

Figure 1. Site plan of Agricultural Engineering Department recharge area.

Five constructed pits located on the outer periphery of the playa lake were used for recharge as well as concentrated storage. The Northwest and Northeast pits, having top dimensions of 100 feet by 250 feet with a depth of 10 feet, were used for recharge studies while the East pit, 40 feet by 200 feet by 12 feet, was never tested because of a lack of runoff water after its construction. The two remaining pits were used primarily for storage.

A multi-purpose (irrigation-recharge) well was available for study during the period of the project. The well was gravel packed and cased with 104 feet of 16 inch diameter casing and 48 feet of 14 inch diameter well screen. No provision was made for the addition of gravel later nor was a vent pipe installed.

The well was connected to a 16 lateral filtration bed located in the playa lake which provided for evaluation of filters for clarification as well as supplying clarified waters for recharge. The laterals were approximately 600 feet long, 37 feet apart and buried at a depth of 3 feet. Each lateral was connected to a common mainline incorporating two valves and a water meter which controlled flow to the well and permitted observation of water quality, quantity, and rate of recharge. The laterals were constructed using four types of pipe with different size and shape perforations, and backfilled with four types of filtration material including gravel, corn cobs, gin trash and cotton burrs, and natural soil.

Four recharge shafts, each with 40 inch diameters but depth varying from 17.5 to 21.5 feet, were available and located within the Northwest recharge pit. The shafts identified as A, B, C, and D were backfilled with 3/4 inch aggregate, 1/4 inch pea gravel, sand, or a combination of all three media.

A trench, 13 inches wide, 3-1/2 feet deep, and 1,000 feet long, was constructed and used in this study. The trench was uniformly graded at a 0.5 per cent slope and incorporated six rectangular weirs spaced approximately 150 feet apart for flow monitoring. The 3-1/2 foot depth penetrated the top layer of soil and exposed varying grades of caliche through its traverse.

During the establishment of an observation well network, the well driller encountered circulation problems in one general location and abandoned the site after drilling to a depth of 30-35 feet. The drilled hole was used extensively in the recharge studies. An additional hole was constructed in the vicinity of the playa lake however it received only preliminary testing. Eight holes with the same basic characteristics were installed at Reese Air Force Base, 8 miles west of the recharge site, and would have been used for similar studies provided runoff water had become available at that site.

A 50 by 100 foot section of the playa lake filtration bed was modified using polyethylene sheeting to attain a one foot deep ponded area. This installation permitted field evaluation of the filter system.

A separate area consisting of four laterals of 4 inch bituminous fiber pipe each 100 feet in length and laid to a 0.5 per cent grade provided further opportunity for clarification study. Two of the laterals were placed at a depth of 2 feet with the other two being set at 1.5 feet. One of each pair of common depth was totally backfilled with 3/4 inch rock aggregate and 1/4 inch pea gravel respectively.

An observation well network consisting of 10 wells was strategically located in and around the recharge area. These locations can best be seen in Figure 1. The wells provided opportunity for monitoring water levels and permitted evaluation of the growth and decay of the ground water mound resulting from recharge operations. All wells extend to a depth of 150 feet below the ground surface and are cased with 2 inch plastic tubing perforated the last 50 feet.

The source of water for recharge was surface runoff which collected in the playa lake. The contributing watershed is an area of approximately 760 acres of mixed culture, one half urban and one half agricultural. The soils of the watershed are fine sandy loams and fine sands with caliche generally found at depths of four to ten feet. The soil in the playa lake bottom was a Randall clay with a very low permeability. Slopes of the watershed ranged from zero to three per cent with the steeper slopes nearest the lake area. During the last nine months of the project the watershed has been significantly altered by new urban development near the recharge area. The new watershed created within the original area has greatly reduced the total amount of runoff collected in the recharge area.

Although rainfall on the watershed is generally limited there are periods of high intensity precipitation which result in considerable runoff. These runoff waters carry a very high sediment load which complicates recharge operations, however permits work toward satisfaction of the stated objectives.

The general procedure for conducting research depends upon the availability of water. If large volumes of water were available several recharge studies were conducted simultaneously in order to make maximum utilization of available resources. With only limited quantities of water, only a small part or phase of the total project was studied.

The usual procedure for recharge was to collect water in the South pit with any overflow entering the playa lake and the North pit. Pit recharge was accomplished by pumping runoff water from the storage pits into either or both the Northeast and Northwest pits. The water entering the recharge pits was metered and its volume recorded. A water stage recorder was used to automatically record rates and volumes recharged. During pit recharge periods observation wells were monitored daily. Maintenance was performed in the pits as required to remove the sediment deposits.

When water was available in the modified playa lake, well recharge operations were initiated generally after a 24 hour settling period. The well was pumped for a short period prior to and during the initial minutes of recharging. After this initial procedure the pump was stopped and recharge commenced. Recharge was generally for a period of 22 hours followed by two hours pumping after recharge to partially remove sediments deposited during recharge. Records of all water level changes at the recharge well and the observation wells and volumes and rates recharged and pumped were kept during the recharge period.

Shaft recharge was affected by pumping from the South or North pit into an 8 foot diameter 6 foot high steel ring placed around the shaft and sealed in the bottom of the pit providing an extremely large infiltrameter. The inflow was controlled and metered. After filling the ring and shaft the flow was slowed to match the recharge rate and to maintain a constant head in the ring. Recharge rates and volumes were determined on the basis of runoff water pumped into the ring. Observation wells were monitored as described earlier.

Hole recharge was accomplished by pumping from the South or North pit through a meter and valve to the top of the hole. By gravity flow, water was allowed to fill the cavity at the bottom of the hole. When the cavity and the hole were filled the flow was slowed to match the recharge rate of the hole. Recharge periods ranged from a few days to in excess of 3 weeks. During the course of the investigation the hole was modified several times in order to determine its most practical configuration.

RESULTS AND DISCUSSION

There were three well recharge periods during this study, which netted approximately 24 acre-feet of runoff water recharged as shown in Table I. The runoff water accumulated in the playa lake had a distinct red color as evidenced by its high sediment content. All water recharged through the well passed through the filter system with the resulting filtrate possessing a cloudy brown appearance caused by the fine clay colloids remaining in the water. During the two hour pumping cycle the water pumped was clear but contained considerable quantities of fine sand

TABLE I. WELL RECHARGE DATA

Period of Recharge	Recharge Rates (Gallons Per Minute)	Volume Recharged (Acre-Feet)	Water Level in Observation Well #1 (feet)*
5-5 to 5-12-69	210[a] 150[b]	3.7	3176.20[c] 3181.70[d]
9-8 to 9-29-69	290 175	9.2	3180.70 3186.90
10-22 to 11-6-69	310 175	11.0	3183.30 3192.45

a - upper number represents maximum rate
b - lower number represents minimum rate
c - upper number represents beginning water level elevation
d - lower number represents water level at termination of recharge
* - above sea level datum

from the Ogallala which was not considered attributable to recharge efforts.

The water level response in the nearest observation well appeared within a few hours after recharge began and it's water level generally rose several feet within the first 24 hours. The decay of the ground water mound was generally slow after well recharge was terminated.

The limiting factor of the well recharge rate was the amount of water which the well would take under free fall conditions. Rates were observed to decrease when flow changed from free fall to full pipe flow into the well. Records indicate the total amount of filter water recharge in the well since 1959 has been over 200 acre feet.

An attempt was made to evaluate the actual filtration ability of the ten year old filter system. The filtration line selected for testing was a 6-inch diameter cement-asbestos pipe with 0.25 inch by 2 inch slits spaced at one foot intervals along the bottom. At the time of installation of this line in the summer of 1959 the filtration material was a 6-inch layer of gin trash and cottom burrs above the line. At the time of inspection in late February 1969, the filtration media had decomposed to a thickness of approximately 1/4 inch above the line. A 3/8 inch layer of deposited sediment covered the inside invert of the filtration line.

A polyethylene sheet pond 50 feet by 100 feet was placed over a section of the line. Approximately three days after water was ponded over the line an insignificant amount of water was noted flowing in the drain. The small volume of water flowing in the line and existing sediment within the line made it impossible to obtain a water sample for comparison with that being pumped into the plastic pond.

The unsuccessful attempt to evaluate the playa lake filtration bed prompted the inspection of the entire system. Three additional lines were selected for re-excavation and study. A 6-inch octagon clay tile originally backfilled completely with natural soil was found to contain approximately 2.5 inches of sediment at its bottom. A 4-inch bituminous fiber pipe which had been backfilled with 6 inches of corn cobs, of which there was no trace, contained 3/4 of an inch of sediment. The final line inspected was 4-inch plastic pipe backfilled with a 6-inch layer of pea gravel. This pipe was plugged by 3/4 inches of sediment and the gravel layer above the pipe was highly sedimented.

Surface inspection of each of the 16 filtration lines revealed several with openings to the surface allowing the direct entrance of runoff water. This fact plus the plugged nature of the inspected lines indicates most of the water recharged from this filtration bed did not actually receive any filtration. The poor conditions of this filtration bed initiated the construction and testing of an entirely new filtration system.

High intensity rainfall inundated the newly constructed filtration bed three times prior to actual testing. Data gathered on the performance of this filtration bed did not produce meaningful results. Further testing is required to produce an accurate conclusion as to the effectiveness of this design.

Extensive testing was conducted on recharge shaft A which extended 21.5 feet below the bottom of the Northwest pit. This shaft was backfilled with 3/4 inch aggregate. The maximum recharge rate observed was 37 gpm with a four foot head. Only a slight increase in ground water level was noted due to the small quantity to be recharged. Higher recharge rates were expected due to the large surface area through which recharge could have occurred. The low rates are attributed to head loss through the filtration material and sediment accumulation in the shaft. The four recharge shafts have significantly improved the recharge rate of the Northwest pit versus the Northeast pit; however, the difference of head between the two pits at the time of testing is an important factor in the difference of recharge rates.

High intensity rainfall in September 1969 allowed a comparative study of the recharge potential of identical recharge pits with and without shafts. Table II shows the results of this test. The Northwest pit average recharge rate was more than double the average rate for the Northeast pit without shafts. As previously reported the lessening wetted perimeter in the pit sides in combination with the sealing of the bottom by sediment are the primary contributing factors to the decreasing rate as the recharge period progressed.

Preliminary investigation was given to a trench as a recharge facility. The trench was filled with runoff water pumped from the South pit and was allowed to flow the length of the pit. Weirs were used to measure flow at various reaches of the trench with differences in flow being considered recharged. During the initial one and one-half hours of testing the recharge rate for the trench was 100 gpm or an average rate of 0.1 gpm per foot of trench length. This rate dropped to 90 gpm for the next 15 hours and to 20 gpm after 22 hours of recharge.

Primary emphasis within the study has been in the area of hole recharge because of the unexpected success encountered in the use of this recharge method. The hole is a 5 inch diameter hole drilled to a depth of 30 feet terminating on a bed of indurated caliche. Actually, two holes exist at the same location, however, only one has been used in recharge studies.

The first attempt to recharge the hole occurred in early May, 1969. For this initial trial, a 2 inch diameter plastic

TABLE II. PIT RECHARGE DATA

Period of Recharge	Pit	Depth of Water (feet)	Volume of Recharge (acre-feet)	Rate Water Level Decline (ft/day) Max.	Min.	Average Recharge for Period (acre-ft/day)
9-2 to 10-3-69	NE	7.90	3.30	1.10	0.19	0.10
9-10 to 10-6-69	NW	10.60	7.05	1.40	0.40	0.27

tube was inserted to the bottom of the hole, but this pipe did not have a flow capacity to equal the apparent recharge potential of the hole. To permit greater recharge rates and also to provide stability to the hole, a 4-inch by 30-foot section of aluminum tubing was placed in the hole. The initial recharge rate was 120 gpm which dropped to 60 gpm and was sustained for the duration of the test. The water level in observation well #4 responded to the recharge with a static water level increase of 7 feet.

A second recharge period occurred beginning June 3, 1969. The initial rate of recharge during this period was 140 gpm dropping to a sustained rate of 90 gpm. Both of these rates were higher than for the previous period of recharge. It became evident during this recharge attempt that a cavity existed at the bottom of the hole being recharged. The cavity size was estimated to possess a volume of 60 cubic feet. Also a cavity immediately beneath the surface was formed and extended laterally to include the second hole.

During the period of late June through September, 1969, three extensive recharge periods were possible. Unexpected success such as an increase in recharge rate for each subsequent recharge period was encountered. Table III shows the recharge rates, volumes recharged and water level response in observation well #4 for these periods as well as providing a summary of all hole recharge.

TABLE III. HOLE RECHARGE DATA

Period of Recharge	Recharge Rates (gpm)	Volume Recharged (acre-feet)	Water Level in Observation Well #4 (feet)*
5-5 to 5-17-69	120[a] 60[b]	2.5	3182.99[c] 3189.99[d]
6-3 to 6-6-69	140 90	1.2	3187.49 3191.69
6-16 to 6-20-69	140 100	2.1	3187.89 3192.59
8-26 to 9-6-69	160 120	4.4	3182.39 3193.49
9-18 to 9-26-69	160 120	2.7	3196.09 3207.29
10-25 to 10-27-69	170 120	1.1	3199.69 3205.09
3-9 to 3-10-70	140 100	0.5	3189.25 3190.83
4-6 to 4-9-70	220 120	0.8	3188.48 3190.03
5-12 to 6-9-70	260 150	12.7	3187.62 3204.86

a - upper number represents maximum rate
b - lower number represents sustained rate
c - upper number represents beginning water level elevation
d - lower number represents water level at termination of recharge period
* - above sea level datum

Indications during this period pointed to an increase in the cavity size which seemed to support the corresponding rate increases. Also noted was a corresponding increase in the cavity immediately below the surface. Excavation of a one foot thick surface layer exposed an irregular cavity with the approximate dimensions of 8 feet by 4 feet by 5 feet deep. To prevent collapse and/or failure of the hole a 12 foot section of 12 inch diameter pipe was placed around the hole to just penetrate a hard caliche layer. The exterior of the pipe was backfilled to assume the appearance shown in Figure 2.

A sixth recharge period became possible in October, 1969, and yielded rates, volumes, and water levels as shown in Table III. After this recharge, a concerted effort was made to determine the size, shape, and appearance of the cavity present at the bottom of the hole. A mechanism permitting lowering of a camera into the hole was developed and pictures were obtained. The hole extends primarily to the southeast with an upward dip of approximately 40 degrees. The depth of the cavity at the hole is approximately 3 feet and total length is about 12 feet. A schematic of its appearance is shown in Figure 3.

In February, 1970 the second hole was re-excavated and the upper 12 feet were cased similar to the first hole. Preliminary indications were that the second hole did not pass through the cavity of the first. The second hole is deeper, 35 feet as compared to 30 feet, and appears to possess an individual

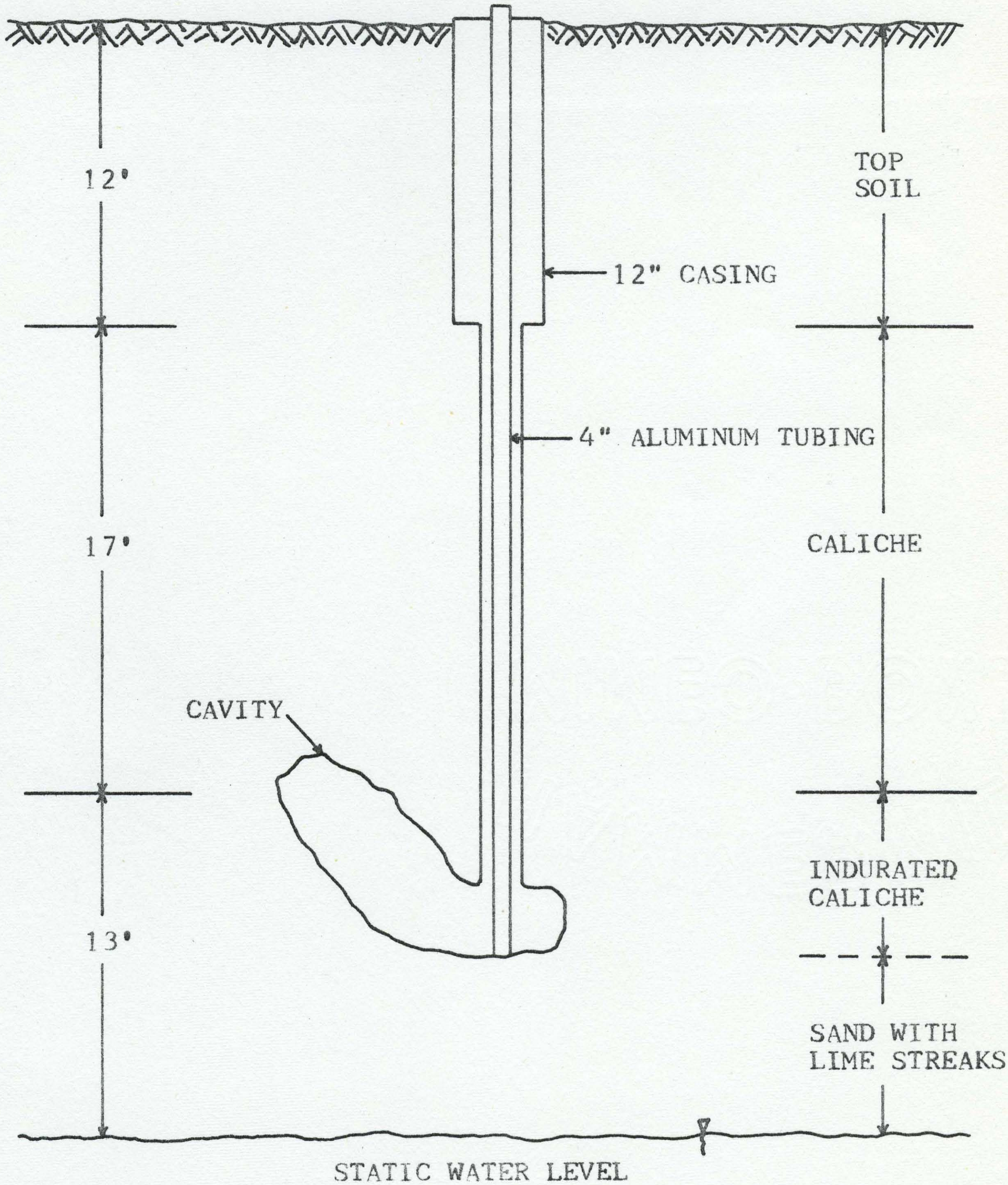

Figure 2. Schematic diagram of hole recharge facility in October, 1969.

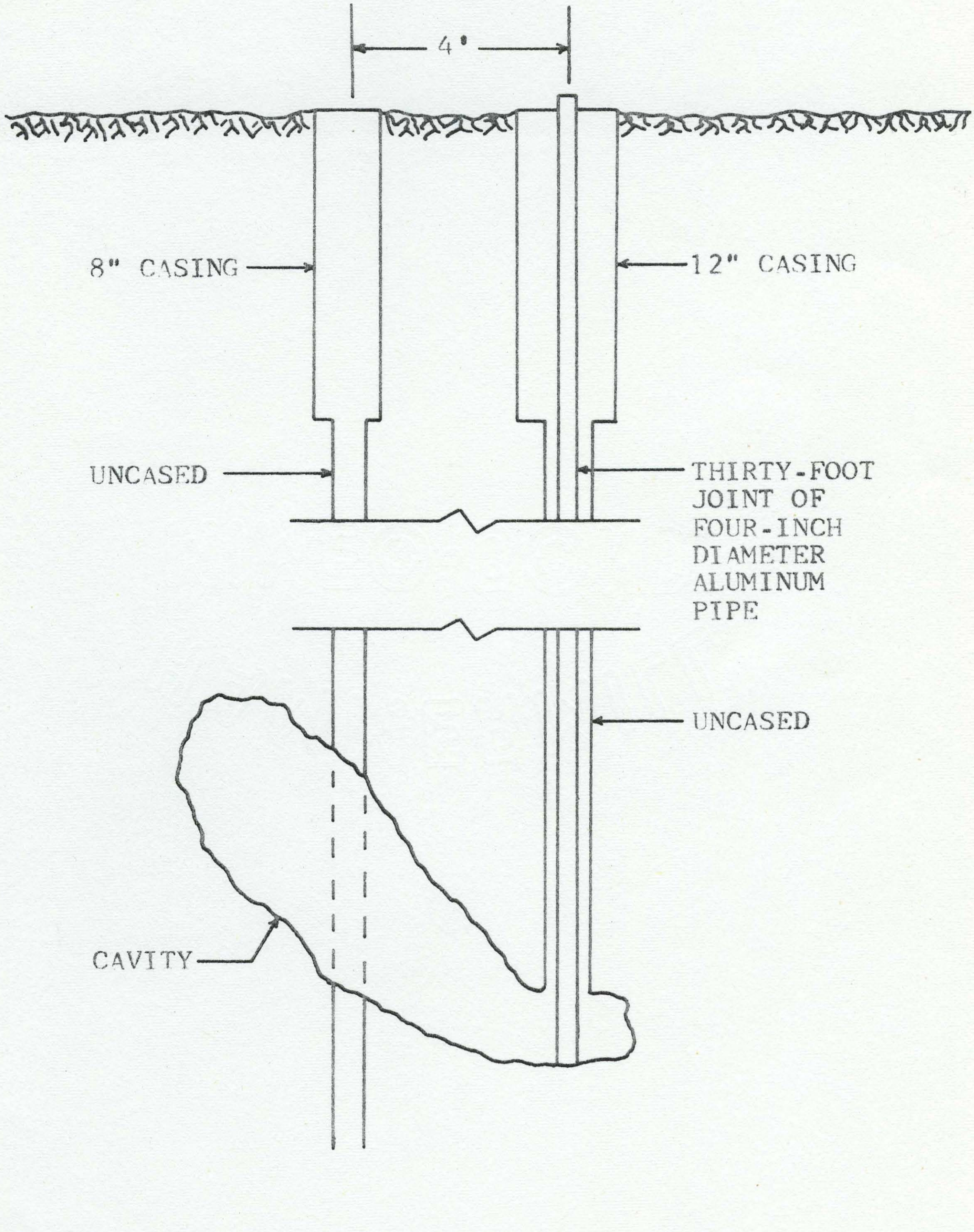

Figure 3. Schematic of cavity and recharge hole, March 1970.

cavity at its terminal. Due to obstructions within the hole, photographic equipment could not traverse the length of the hole, thus this cavity is unconfirmed.

Two short period recharge sequences were conducted in March and April, 1970. The first of the periods produced a decline in rate of recharge however, this may be attributable to material falling into the hole and cavity during re-excavation of the second hole. The April recharge period produced the highest initial rate of recharge (220 gpm) recorded to that date. This rate declined to 120 gpm within a short period with the 120 gpm being an increase over the March sustained rate. This fact, plus others evidenced during recharge, now indicate entry of the second hole into the cavity of the first. Also some changes have been noted in the shape, size, and appearance of the cavity.

The most significant hole recharge test occurred during the period from May 12 to June 6, 1970. This trial resulted in 12.7 acre feet of runoff water recharged at rates above 150 gallons per minute. No further tests have been conducted on this hole because of a lack of runoff producing precipitation.

A recharge hole constructed to the northeast of the original hole installation was briefly tested under both gravity and pressure injection. Both attempts proved unsuccessful, however, the total pump time for both tests was less than one hour.

The eight holes drilled at Reese Air Force Base have not been tested because of a lack of precipitation and runoff at this location. Figure 4 shows the basic characteristics of these recharge holes.

Within a period of approximately one year, more than 28 acre-feet of turbid water has been recharged through the recharge hole. Rates have increased since the beginning, probably due to the enlargement of the cavity below the ground. The enlargement may have been created by the dissolving of the caliche material, thus creating solution channels. Enlargement has been substantiated by pumping estimates and by photographs.

During all tests turbid water was used. The runoff water contained large amounts of suspended particles and to date does not appear to be limiting recharge.

In Figure 5 the growth and decay of the ground water around the recharge hole can be seen for two selected periods of recharge. As the ground water level intercepted the bottom of the hole, the rate did drop due to the change, from unsaturated to saturated flow. For this reason, and the fact that approximately 6 cubic yards of top soil apparently was piped into the hole, the increase in rates slowed through September. Except for one period, in March, the recharge rates have generally increased.

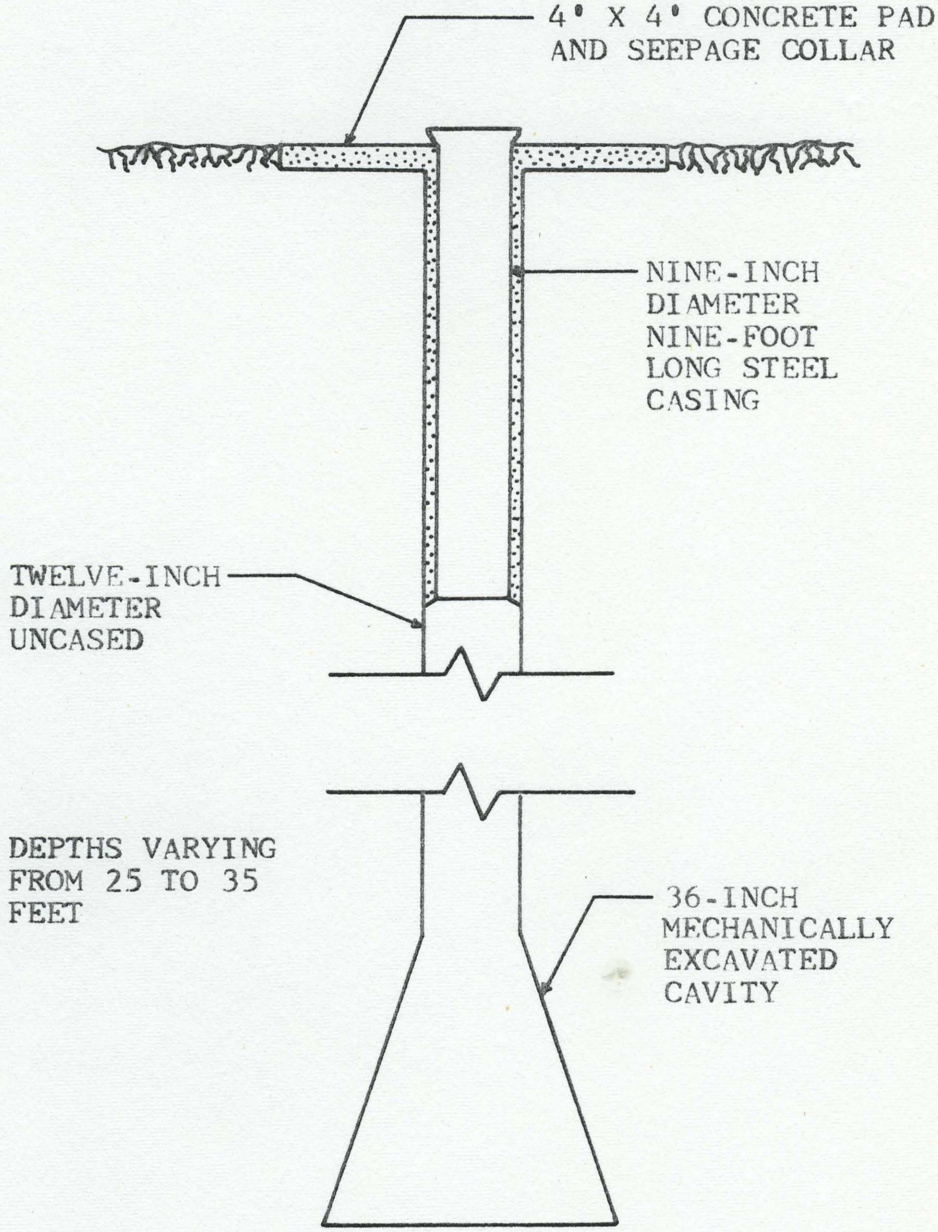

Figure 4. Schematic of recharge holes at Reese Air Force Base

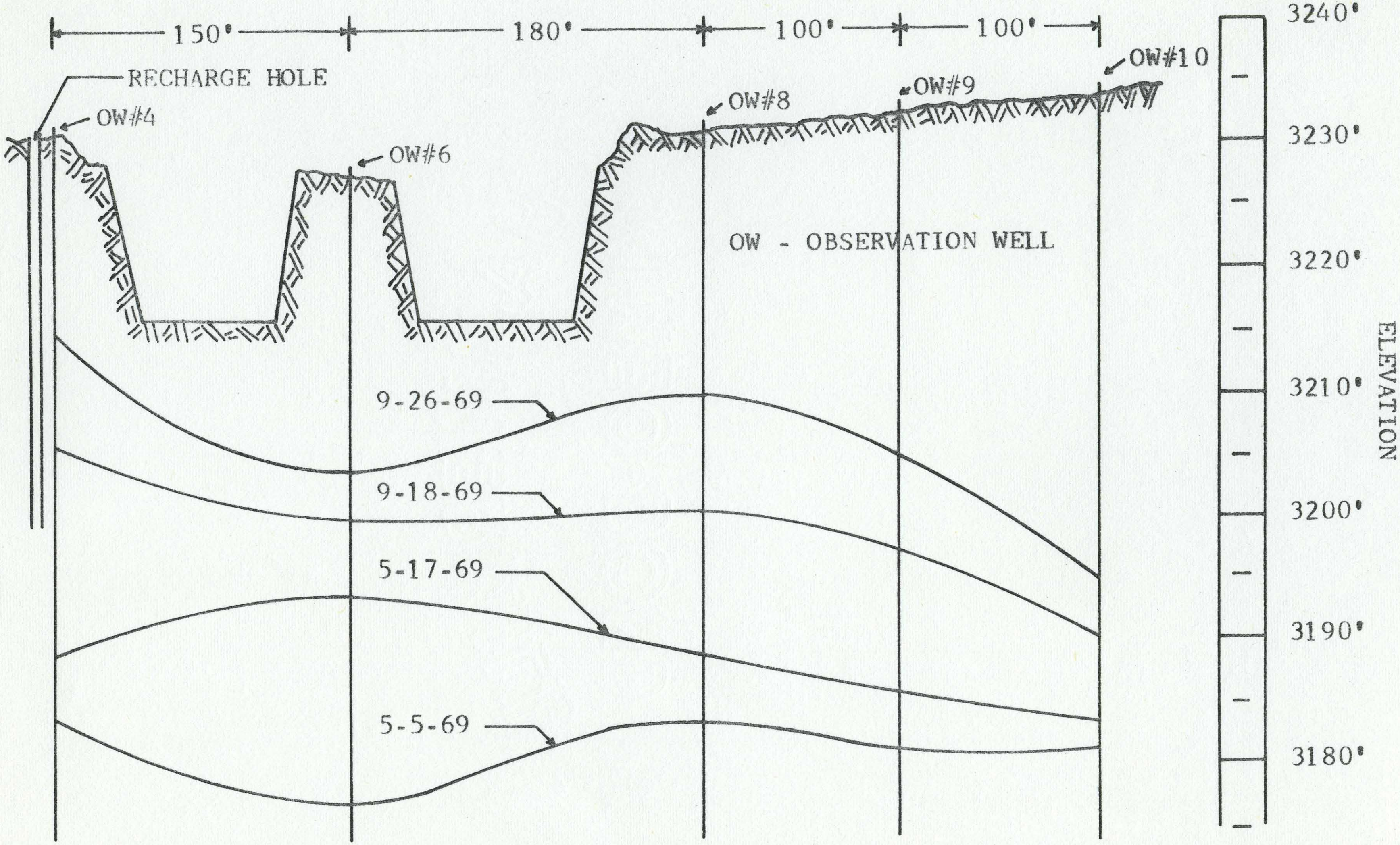

Figure 5. Ground water mount growth and decay in response to the recharge hole.

SUMMARY AND CONCLUSIONS

Water is the most important limiting factor to agricultural production and economic growth in the Southern High Plains of Texas. The use of ground water from the Ogallala Formation has helped to remove these water limitations but the remaining water in the Ogallala Aquifer is rapidly being depleted. Artificial recharge methods presently being investigated offer the potential to manage and conserve both surface water and ground water resources.

The research conducted within this study has been concentrated on the removal of sedimentation as a restriction to artificial recharge. Data obtained through these investigations will assist in the development of design criteria for technically and economically feasible ground water recharge systems.

Gravity flow recharge wells appear to be an effective means of recharge, provided sufficient care in both design and operation are taken. As particle size of the aquifer decreases, increasing attention should be given to the possible effects of the introduction of foreign materials into the formation.

Filtration systems offer a positive alternative to proper design and operation; however, their inefficiency and economic cost generally make them unacceptable for use in most recharge operations. Stilling periods of adequate duration to allow for the settling of a large portion of the suspended solids, seem to be the most reasonable substitute for filtration or clarification.

A trench of the configuration used in this study was ineffective as a means of recharge. The failure of this system may be attributed to the shallow depth to which the trench was dug. It is felt that modification of the trench to the depth utilized by the recharge pits in this study would have improved the performance of this facility. The self-cleaning nature of the vertical side walls and the economy of construction and cleaning by means of a trenching machinery offer excellent potential for future recharge utilization.

The use of recharge shafts was disappointedly unsuccessful in this study. The removal of the backfilled filtration material, thereby reducing the head loss in the shaft, may improve the recharge rate possible through the shaft; however, the elimination of the filtration material and the injection of large quantities of turbid water greatly increase the possibility of plugging by sediments as well as physical collapse of the shaft. The success encountered in the use of a similar mechanism, small diameter shallow holes, has diminished the relative importance of shaft recharge in this study.

Small diameter shallow holes have shown tremendous potential for ground water recharge at the test site location. The ability of this mechanism to recharge large volumes of unfiltered runoff water at moderate rates with no apparent detrimental effects, at a minimum expenditure for its installation and operation greatly enhance its potential usefulness. Recharge holes similar to those used in this study have the advantage of recharging water above the aquifer, and thereby reducing or eliminating potential physical pollution of the aquifer in comparison to that which could be anticipated by direct injection of the water into the formation.

If hole recharge can be duplicated in other areas, a new and economical method of recharge with tremendous potential has been developed. The ability to duplicate this method seems dependent on the artificial formation of a cavity allowing infiltration over a large surface area, in a highly permeable strata and the control of this excavation process once it is begun.

Ground water levels in the test site area have been appreciably increased during the course of this study, even though this area is also subject to moderate ground water withdrawals. This increase contrasts with the general situation of the Southern High Plains where water levels are declining annually.

Sedimentation continues to be a significant problem to artificial ground water recharge. The complexity and severity of the problem is generally greatest in well recharge and strongly dependent upon the particle size in the aquifer. Pits and trenches are also effected by sediments; however, annual or periodic maintenance retains their recharge ability. Hole recharge requires further development in order to realize its potential as a recharge mechanism.

RECOMMENDATIONS

Wells remain an effective means of recharging underground formations. Because of the direct injection of recharge waters into the aquifer by this method, sufficient care in the design and operation of any recharge well is strongly recommended in order to prevent physical pollution of the formation. The design and operation criteria should be based on the magnitude of the sediment load of the recharge waters and the particle size of the aquifer to be recharged.

Pits and trenches serve as excellent means of ground water recharge provided maintenance is performed as required to remove sediment deposits. The recharge potential of either type facility is highly dependent on the permeability of strata into which they extend and the degree to which they extend into these strata.

Hole recharge appears to be a mechanism of significant potential. This method of recharge possesses a low capital investment requirement, little or no maintenance requirements, and the ability to recharge runoff water at moderate rates with no filtration or clarification. Further study is needed to evaluate the continued and universal effectiveness of this recharge mechanism.

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