Testing Procedures and Results of Studies of Artificial Recharge in the Grand Prairie Region Arkansas

By R. T. SNIEGOCKI, F. H. BAYLEY 3D, KYLE ENGLER, *and* J. W. STEPHENS

ARTIFICIAL RECHARGE OF GROUND WATER—GRAND PRAIRIE REGION, ARKANSAS

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1615-G

Prepared in cooperation with the U.S. Army Corps of Engineers and the Agricultural Experiment Station, University of Arkansas

---

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1965

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 25 cents (paper cover)

CONTENTS

ILLUSTRATIONS

TABLE

ARTIFICIAL RECHARGE OF GROUND WATER—GRAND PRAIRIE REGION, ARKANSAS

TESTING PROCEDURES AND RESULTS OF STUDIES OF ARTIFICIAL RECHARGE IN THE GRAND PRAIRIE REGION, ARKANSAS

By R. T. Sniegocki, F. H. Bayley 3d, Kyle Engler, and J. W. Stephens

ABSTRACT

Two differently constructed wells were used to make 23 recharge tests, all but one using surface water treated in various ways. The degree of water treatment used in early tests was reduced in some of the later tests. Slightly more than 23 million gallons of water was recharged during the series. A summary of the procedures and pertinent data for each test are given in this report.

A prerequisite to successful recharge through a well at the test site was the availability of a supply of water having very low turbidity and few micro-organisms. An analysis of the cost of recharge through wells, based on the results of this study, showed that water which had been recharged and recovered for use would cost more than $30 per acre-foot. The major item contributing to the total recharge cost was the treatment of an injection supply to obtain water having low turbidity and few micro-organisms.

A coarse-grained media filter might be used to reduce water-treatment costs of some waters. However, the results of filtration tests at the recharge site were unsatisfactory, apparently because of unknown filtration characteristics of the injected supply.

INTRODUCTION

PURPOSE OF THIS REPORT

In 1953 the Grand Prairie region of Arkansas was selected for an investigation of fundamental principles of recharging ground-water reservoirs through wells. The investigation consisted of collecting detailed hydrogeologic information in the vicinity of the recharge site, drilling two recharge wells, constructing water-treatment and conveyance facilities, and making a series of injection tests in the two wells.

This report is one chapter of a series that covers distinct elements of the project; each chapter was prepared as the data and interpretive analyses became available. The previously published parts of this series on artificial-recharge tests in the Grand Prairie region are chapters A–F of U.S. Geological Survey Water-Supply Paper 1615. The purpose of this report is to present a summary of testing procedures, the pertinent data collected, the results of each injection test, and an estimate of the cost of recharging by methods used in this study. Pertinent chemical-quality data collected during this study are given in Water-Supply Paper 1615–E (Sniegocki, 1963a).

PROJECT LAYOUT

Equipment specifications and control points are discussed in another report (Sniegocki, Bayley, and Engler, 1963). However, as an aid in following the résumé of the tests, specifications of the recharge wells are shown in figure 1, and the physical layout of equipment and control points is shown in figure 2.

ACKNOWLEDGMENTS

The cooperation, assistance, and advice given by many Federal, State, and city agencies, by companies, and by individuals are gratefully acknowledged. Detailed accounts of assistance were given in Engler, Bayley, and Sniegocki (1963) and in Sniegocki (1964).

TESTING PROCEDURES AND RESULTS

Initial planning envisioned the use of treated surface water in the early recharge tests; in later tests the degree of water treatment was to be reduced until the recharge well became clogged. Ground water was used as the injection supply for the first recharge test, to determine the hydraulic characteristics of buildup in and around the recharge well under favorable conditions. In subsequent recharge tests, surface water was used as the injection supply.

Two recharge wells were used for injection tests. (See fig. 1.) The design specifications of recharge well 1 are similar to those of many irrigation wells now (1960) in use in the Grand Prairie region. Recharge well 2 was designed specifically for testing purposes and included special equipment to facilitate redevelopment between injection tests. A detailed description of both recharge wells was given by Sniegocki, Bayley, and Engler (1963).

During this study, 23 recharge tests were made—17 in well 1 and 6 in well 2. A summary of the tests and pertinent data for each are given in table 1.

RECHARGE WELL 1

TEST 1

Recharge test 1 was made using ground water for the injection supply. The purpose of the test was to check values of the coefficients of transmissibility and storage previously determined by a pumping

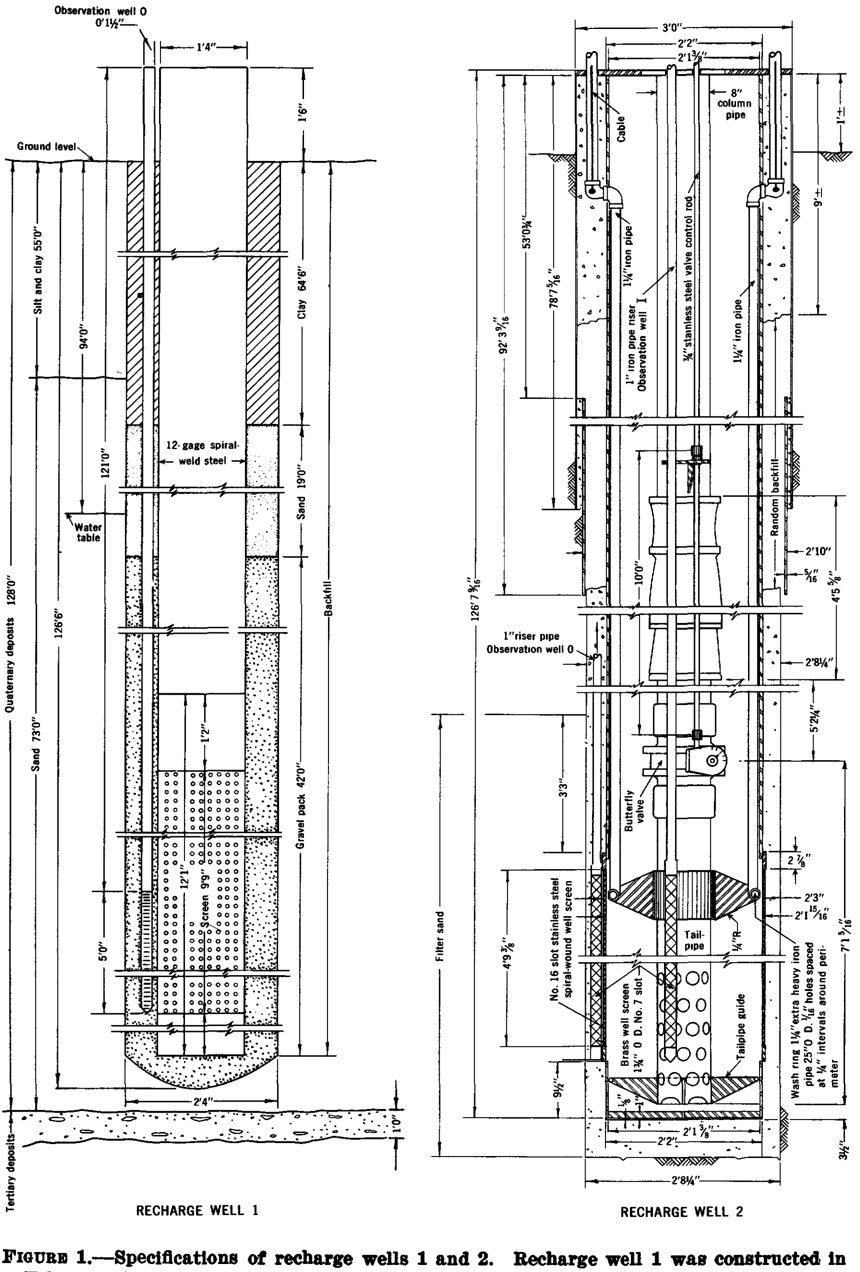


Figure 1.—Specifications of recharge wells 1 and 2. Recharge well 1 was constructed in February 1955 and was used in artificial-recharge tests 1–17. Recharge well 2 was constructed in July 1958 and was used in tests 18–22.

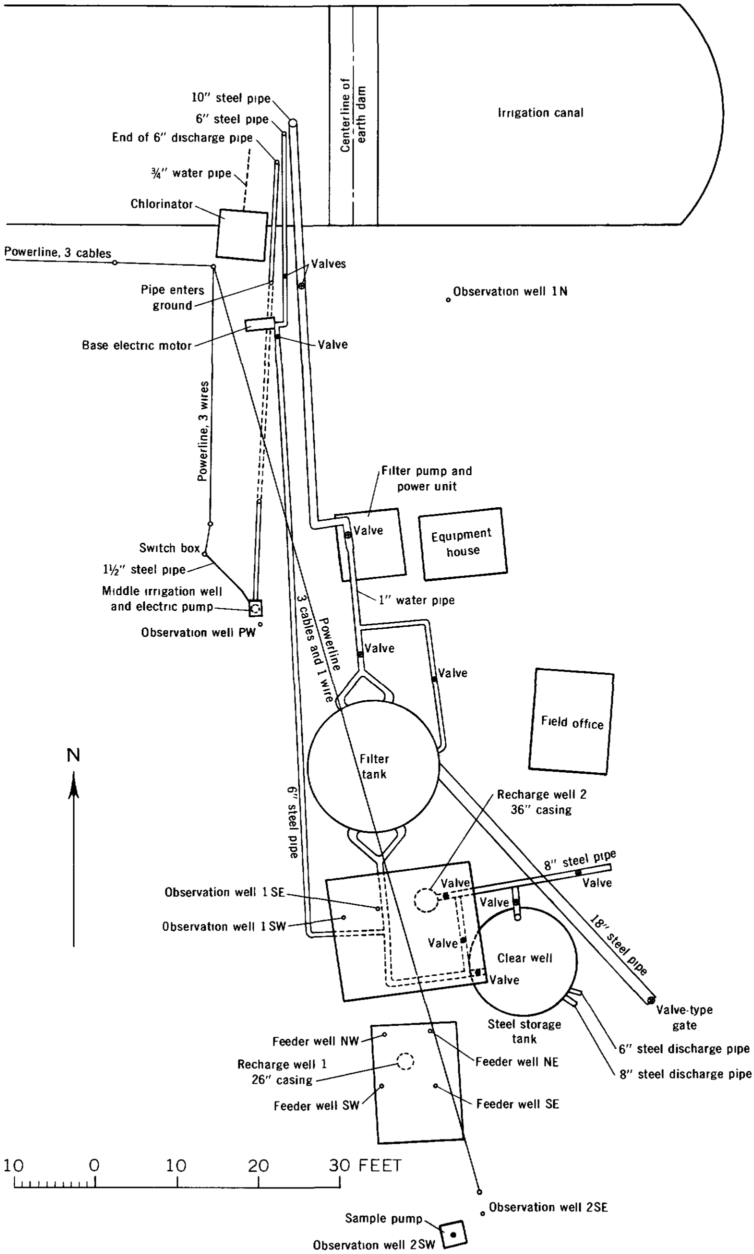


FIGURE 2.—Artificial-recharge site, showing equipment layout.

test, to develop operational techniques to be used in later recharge tests, and to learn whether an aquifer could be artificially recharged through a well at a practical rate under favorable conditions.

An irrigation well a quarter of a mile east of the recharge well was used as the source of the ground-water supply. The well is 127 feet deep and yielded about 600 gpm (gallons per minute) through an electrically powered turbine pump. Chemical analyses of water samples from this well and from the recharge well showed a similarity of composition. A valve on the discharge pipe was used to control the rate of discharge of the pumped well during the injection test. Approximately 1,600 feet of aluminum irrigation pipe was coupled to convey the water to the recharge well. The water was fed into the recharge well by gravity through the pump column of a turbine pump installed in the recharge well.

No hydraulic interference between the recharge well and the well furnishing the injection supply was anticipated if the pumping-recharge rate was limited to 500 gpm for 12 days or less. Therefore, recharge test 1 was planned for termination at the end of 12 days.

Water-level measurements were made with a steel tape in the observation wells that were measured in the pumping test (Sniegocki, 1964). Corrections for atmospheric-pressure changes and for filling the aquifer (as opposed to a decrease in saturated thickness during the pumping test) were applied to all measurements before they were used in hydraulic computations. The correction for the change in saturated thickness was negative under drawdown conditions and positive under buildup conditions. Corrections of water-level measurements for increase in saturated thickness ranged from 0 to 6.7 feet depending upon time elapsed after beginning recharge and upon distance from the recharge well.

The Theis (1935) method was used to compute the transmissibility and storage coefficients after 1,800 minutes (1,25 days) and after 5,760 minutes (4 days) of recharge. The coefficient of transmissibility was about 67,000 gpd per ft (gallons per day per foot) and the coefficient of storage was about 0.14 at 1,800 minutes. At 5,760 minutes the coefficient of transmissibility was about 63,000 gpd per ft and the coefficient of storage was about 0.28.

The transmissibility and storage coefficients calculated from pumping-test data at 1,920 minutes were about 70,000 gpd per ft and 0.18, respectively. The transmissibility value calculated from recharge data compares well with that calculated from pumping-test data. The value for the coefficient of storage calculated from either recharge or pumping-test data is valid only for the time at which it is calculated. Presumably, under pumping conditions the change in the value of storage with time is the result of slow drainage caused by the presence of thin lenses of clay and silt of limited extent in the aquifer and by

TABLE 1.—*Summary of recharge tests and pertinent data*

[Tests 1–17, recharge well 1; tests 18–23, recharge well 2]

Test	Date	Water treatment	Average chlorination rate (lb per day)	Average turbidity (ppm)	Average temperature of water (°F)	Average rate of recharge (gpm)	Quantity of water recharged (gal)	Duration of test (min)	Specific capacity of well before test (gpm per ft)	Specific capacity of well after test (gpm per ft)	Remarks
1	3-9, 14-55	Ground water injected into well; no treatment.	None	No record	65.5	512	3,619,990	7,065	21	7	Test made with ground water pumped from an irrigation well a quarter of a mile from the recharge well.
2	3-28-56 to 4-2-56.	Water pretreated with alum, chlorinated, and filtered.	12.7	15.3	59.5	490	2,528,900	5,163	25	7	Sodium fluoride (1 ppm) added to recharge water as a tracer; tests 2-23 made with surface water.
3	10-10-56	do	30.0	2.6	65.5	297	39,800	134	31	12	Calcium chloride added to recharge water to change cation-anion ratio; sodium hexametaphosphate added to prevent iron precipitation; air allowed to enter injection line during tests 3 and 4.
4	10-24-56	do	28.4	3.9	68.6	289	46,250	160	25	11	
5	11-7-56	Water pretreated with alum, and chlorinated; not filtered.	11.5	6.2	65.0	289	104,100	360	26	25	Air not allowed to enter injection line during test; injected water pumped out; no redevelopment.
6	11-28-56	do	9.1	2.7	43.0	294	105,900	360	27	12	Air allowed to enter injection line; after test, well redeveloped with sodium hexametaphosphate solution.
7	12-5-56	do	11.5	3.2	58.3	305	109,800	360	25	30	Air not allowed to enter injection line during test; no redevelopment attempted after test.
8	1-9-57	do	14.7	5.7	59.5	496	178,500	360	30	27	No redevelopment after test; injected water pumped from aquifer after test; air excluded.
9	1-30-57	Water chlorinated	10.3	15.9	41.7	510	158,200	310	27	12	Test made with turbid water to check relative plugging effect; air excluded.
10	2-12, 15-57	Water pretreated with alum, and chlorinated.	26.9	7.3	56.4	498	972,840	1,952	27	8	Well backflushed by pumping after each period of recharge; air excluded.
11	2-19-57	do	40.0	16.9	No record	303	81,900	270	25	12	Air allowed to enter injection line to check possible dissipation after entrainment.

12	10-11-57	Water pretreated with alum, chlorinated, and filtered.	23.8	2.1	65.7	502	180,600	360	30	33	Surface water treated with copper sulfate before pretreatment with alum, to control micro-organisms; air not allowed to enter injection line during tests 12-23.
13	10-25-57 to 11-3-57.	do	16.0	2.4	57.1	505	6,128,800	12,142	33	18	Copper sulfate used to control micro-organisms.
14	1-22-58	Water chlorinated and filtered.	20.8	50+	36.8	117	84,500	720	31	21	Recharge rate lower during test 14 than during preceding tests; well redeveloped at end of test.
15	2-26-58	do	30.9	27.0	55.1	312	224,400	720	28	26	Well was pumped at end of test; no redevelopment attempted.
16	3-25-58	do	45.0	65.0	52.5	545	229,100	420	26	23	No redevelopment attempted after test.
17	3-26-58	do	45.0	50+	50.0	860	162,000	180	23	22	Do.
18	1-29-59 to 2-2-59.	Water pretreated with alum, chlorinated, and filtered.	9.1	3.0	43.0	310	534,700	1,710	27	17	Water treated with chlorine instead of copper sulfate before addition of alum, to control micro-organisms; No plugging indicated during tests 18 and 19, when corrections for lowered water viscosity applied.
19	2-19, 24-59	Water chlorinated and filtered.	19.9	57.0	45.0	313	788,670	2,520	26	20	
20	3-10, 29-59	Water chlorinated	20.0	80.0	54.1	232	5,955,500	25,726	20	2	Water siphoned into recharge well from settling canal.
21	11-5, 6-59	do	21.0	70+	59.7	274	407,600	1,490	17	8	Rate of recharge controlled by value at discharge side of pump.
22	1-26-60 to 2-10-60.	do	6.0	55.0	47.0	37	819,895	22,450	15	2	Very low recharge rate compared to other tests.
23	2-2, 3-61	Water chlorinated and filtered.	10.8	67.8	41.5	145	216,250	1,495	20	11	Rapid sand filter used in preceding tests when water treatment included filtration. Coarse-grained media filter used in this test.

differences in vertical and horizontal permeability. Under recharge conditions the change in the value of storage with time presumably is the result of incomplete saturation of the aquifer, which also is caused by the silt and the clay lenses and by differences in vertical and horizontal permeability in the aquifer.

However, a value of the coefficient of storage equal to the specific yield was approached more rapidly under recharge conditions than under pumping conditions. The coefficient of storage was 0.30 after cyclical recharge for about 9 days, whereas in the discharge situation a value of 0.30 would not be obtained until pumping had continued for more than 100 days (Sniegocki, 1963b).

Evaluation of recharge test 1 and the pumping test showed that water-level rises resulting from recharge through a well may be satisfactorily predicted from pumping-test data.

Hydrographs of water levels inside (observation well I) and immediately outside (observation well O) the recharge well and in a well (observation well 1–SW) 20 feet from the recharge well are shown in figure 3. No apparent plugging of the recharge well occurred during the first 4 days of recharge at 512 gpm. Departures of the hydrographs from smooth buildup curves are caused by injection-rate variations and differences in the time at which the wells were measured.

A "step test" (Sniegocki, Bayley, and Engler, 1963), designed to determine the specific capacity of the recharge well under various injection rates, was to be done at the end of the proposed 12-day recharge period. However, recharge test 1 was terminated by a temporary power failure after 7,065 minutes (about 5 days) and the "step test" was made at that time. The pump on the irrigation well furnishing injection water was restarted and the valve controlling discharge was set for 416 gpm. Water-level measurements were made in observation wells I and O at 12, 15, 20, and 27 minutes of elapsed time. The injection rates were then decreased in turn to 297, 161, and 155 gpm, and water-level measurements were made at the same time intervals, after each rate change. While recharging at 297 gpm, the depth to water in I was 61.28 feet and in O it was 66.55.

The depth to water in I and O at the end of 4 days of recharge at 512 gpm was 74.24 and 74.67 feet (fig. 3). Thus, within the recharge well (I) the water level was approximately 13 feet higher during the "step test" even though the recharge rate was lower. The head difference between I and O was 0.43 foot when recharging at 512 gpm (fig. 3) and 5.27 feet when recharging at 297 gpm; plugging within the recharge well and possibly at some point beyond observation well O was thus indicated.

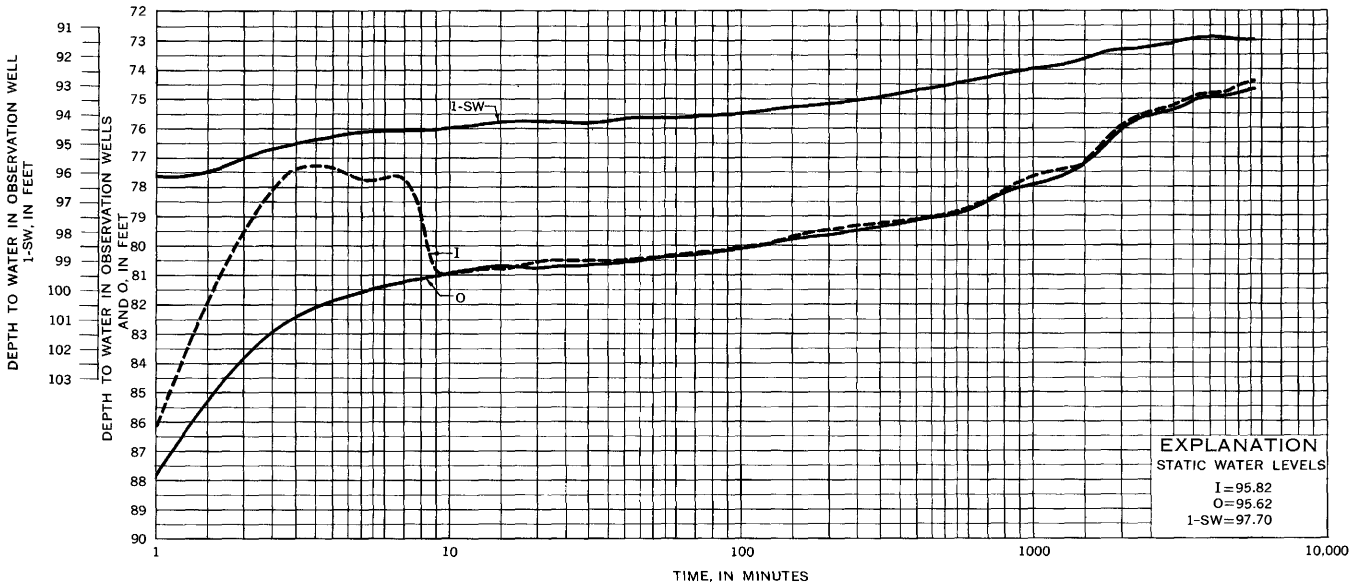


FIGURE 3.—Depth to water in observation wells during recharge test 1. I, inside of recharge well; O, immediately outside of recharge well; 1–SW, 20 feet from recharge well.

Later tests confirmed that the lowered recharge rate of 297 gpm permitted air to enter joints in the irrigation pipe; the well was thus clogged by air entrainment and iron precipitated from solution by aeration. Furthermore, no sand trap was placed in the pipeline conveying water from the irrigation well to the recharge well and minor amounts of sand were found in the pipeline upon disconnecting joints. Therefore, minor plugging probably was caused by sand pumped from the supply well.

Recharge test 1 proved the technical feasibility of recharge through a well at a practical rate when the water used for injection was physically and chemically compatible with the aquifer and native ground water. The recharge well did not become plugged severely until entrained air and precipitated iron were carried into the well with the injected water during the "step test." The specific capacity of the recharge well was lowered from 21 to 7 gpm per ft of drawdown. Successful redevelopment after test 1 brought the specific capacity to 25 (Sniegocki, 1963b).

TEST 2

Recharge test 2 was made with treated surface water to determine if the treatment was sufficient to permit recharge with surface water for long periods of time with little or no difficulty.

Surface water had been pumped from a drainage ditch and stored in a farm canal and reservoir before the test. Aluminum sulfate was added to the water as a flocculant at a rate of 6 grains per gallon of water. After addition of the aluminum sulfate, the floc was allowed to settle. The water was then chlorinated, filtered, and introduced by gravity into recharge well 1 through the pump column of a turbine pump installed in the recharge well. One ppm sodium fluoride was added to the recharge water to serve as a tracer.

Some of the data collected during test 2 are shown in figure 4. The rise and decline of water levels in observation wells (fig. 4) in the first few minutes of recharge were due to a faulty valve setting. Considerably more than 500 gpm was allowed to enter the well while the valve setting was changed. The rate of recharge was adjusted to approximately 500 gpm, and from 10 to 100 minutes of injection the rate of change of head in the recharge well was similar to that observed during recharge with ground water when plugging was negligible. During the period of recharge from 100 to about 1,100 minutes, the rate of change of head in the recharge well progressively increased and the intake specific capacity decreased.

Recharge test 2 was planned for injection at approximately 500 gpm for 2 weeks; however, severe plugging necessitated stopping the test after about 4 days. At the conclusion of the test the specific capacity of the recharge well was 7 gpm per ft of drawdown as compared to a pretest value of 25.

Plugging in this test was the result of a combination of several factors. The following conditions may have contributed to the plugging: Turbidity of the injected water, dispersion of clay lenses in the aquifer, precipitation of iron from the native ground water and injected water, and release of dissolved gases from the injected water.

The turbidity of the injected water, higher than desired, ranged from about 1 to 35 ppm and averaged about 15 ppm. The high turbidity of the filter effluent was the result of improper filter operation. The filter was connected directly to the intake line in the recharge well. The siphon effect that was created as water entered the well operated on the filter system and increased the head loss through the filter (Sniegocki and Reed, 1963). Water with high turbidity passed through the filter and into the recharge well.

Conclusive evidence of ion exchange and resultant clay dispersal was lacking. Chemical analyses of samples of water recovered from the recharge well after recharge showed an increase in the calcium and magnesium content and little change in the sodium content (Sniegocki, 1963a). However, these samples may have represented a mixture of native ground water and recharge water that caused the change in calcium and magnesium content.

The first water pumped from the recharge well during redevelopment contained as much as 6.4 ppm iron, whereas the injected water contained from 0.12 to 0.37 ppm iron and the native ground water contained about 2 ppm. A sample of water taken from the recharge well after pumping for 6 minutes contained only 0.78 ppm iron. Apparently, some precipitated iron that became lodged on the well screen was the cause of minor plugging during recharge, but it was flushed out upon pumping.

The results obtained from the use of sodium fluoride as a tracer were not satisfactory. The specific capacity of the recharge well had been lowered by plugging during the injection test, and it was not possible to recover the injected water during a practical period of time. Therefore, sodium hexametaphosphate was added to the well as a redevelopment chemical, and the well was satisfactorily redeveloped to a specific capacity of 31 gpm per foot of drawdown. Analyses for fluoride were not made after the addition of the redevelopment chemical, because phosphate in excess of 2 ppm tends to interfere with the fluoride determination. After the addition of the sodium hexametaphosphate, the phosphate content was 369 ppm.

The temperature recorder showed that the injected water ranged from 56° to 64°F and had an average temperature of 59.5°F. The temperature of the native ground water before test 2 was 64°F. The

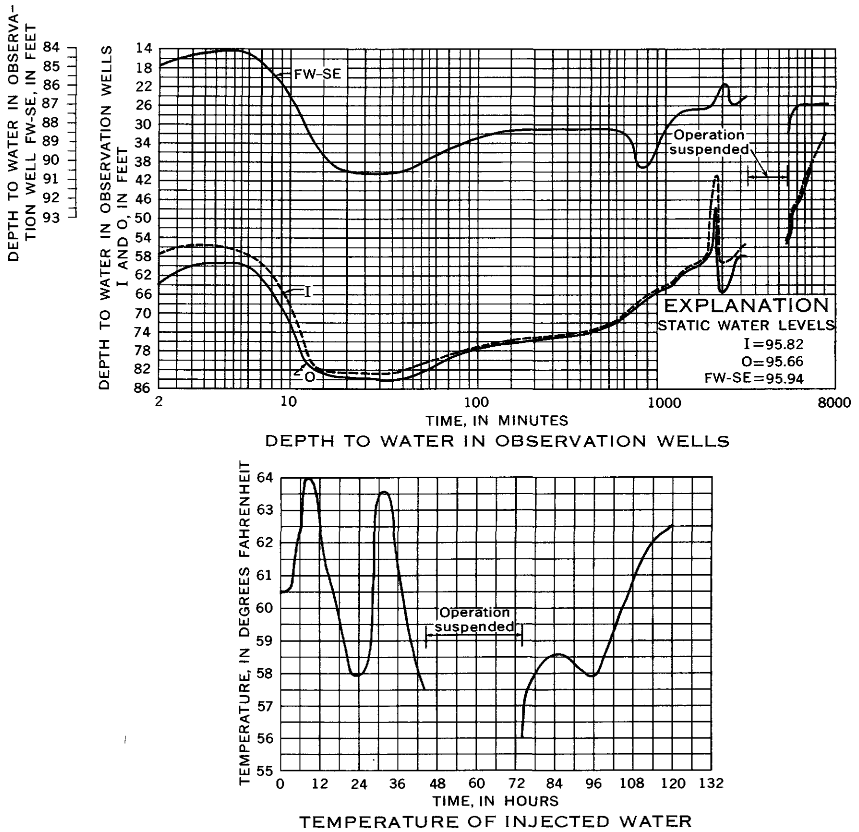
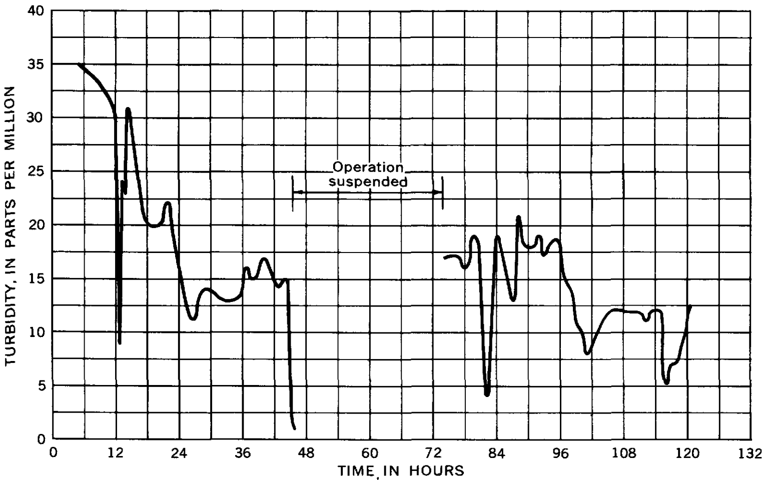


FIGURE 4.—Graphs (above and opposite page) showing depths to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 2. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

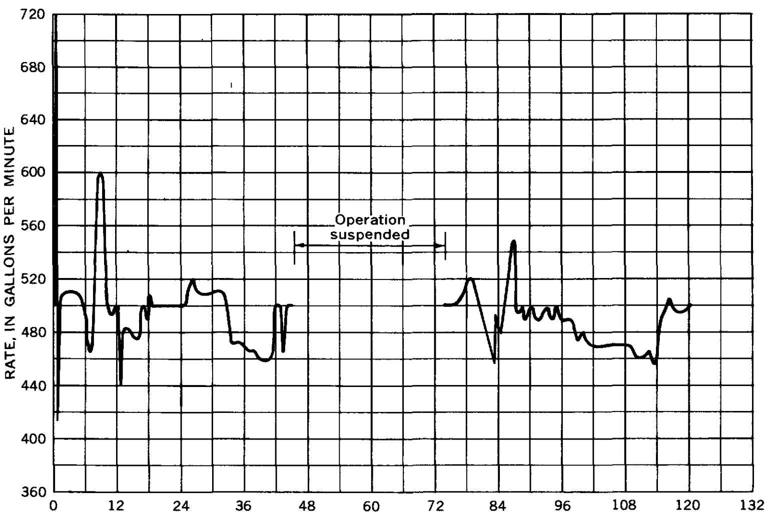
temperature recorder was in operation during the preliminary steps taken to redevelop the recharge well; the initially recovered water was 60°F.

The temperature of the ground water was about 4° higher than that of the injected water. Conditions were therefore, favorable for the release of dissolved gases in the injected water as it was warmed from contact with the warmer native ground water. However, any gases released probably did not measurably decrease the well's ability to take water.

The injected water was removed from the aquifer. Approximately 2.5 million gallons of water was pumped from the recharge well during redevelopment. The temperature of the recovered water showed a very slow rise from 60° to 64°F as pumping progressed. The tem-



CHANGE IN TURBIDITY OF INJECTED WATER



RATE OF INJECTION

perature difference between the injected water and native ground water was used to estimate when the injected water had been removed. A difference in chloride and sulfate contents of the ground water and the recharge water indicated complete removal of the injected water from the aquifer.

TEST 3

Recharge test 3 was planned to eliminate, if possible, the causes of clogging suspected during test 2. The recharge rate was to be lowered from 500 to 300 gpm to increase filter efficiency and make fewer

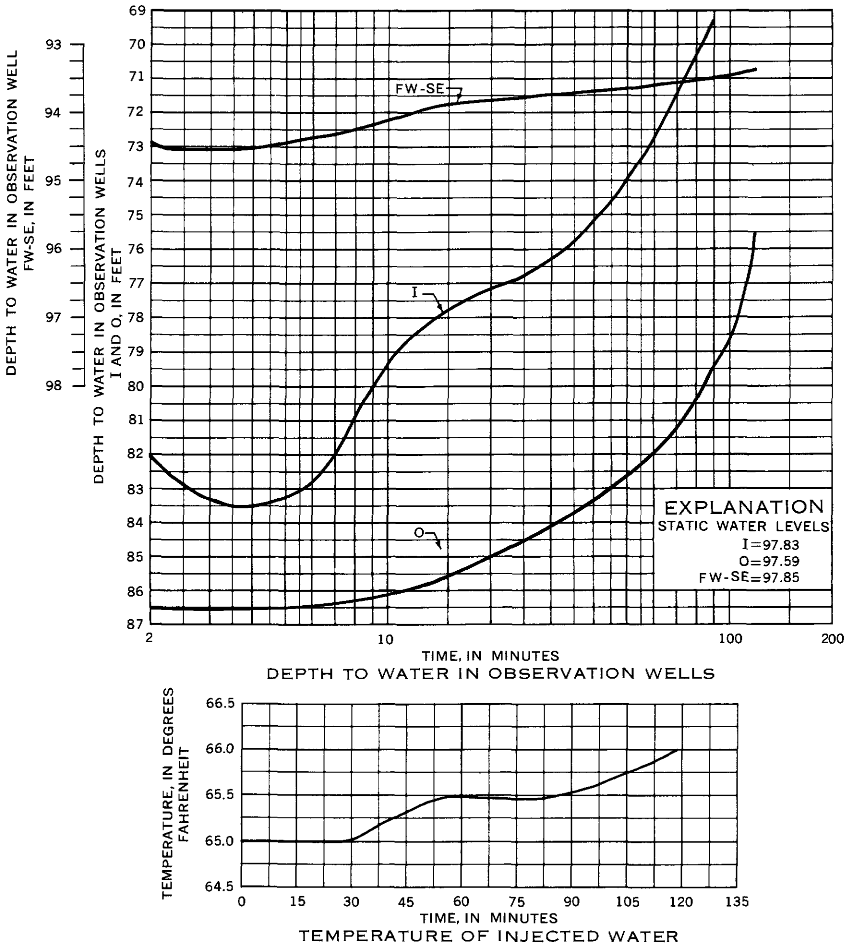
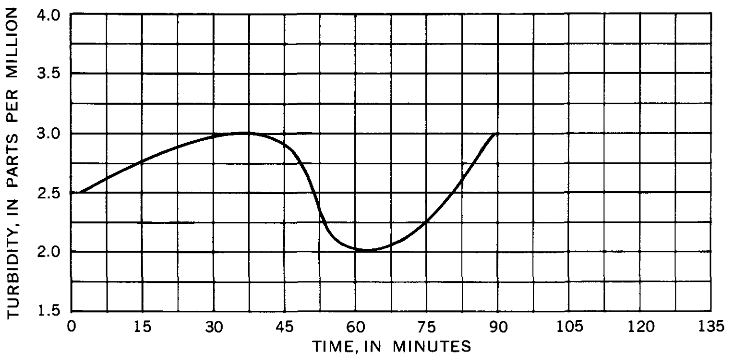


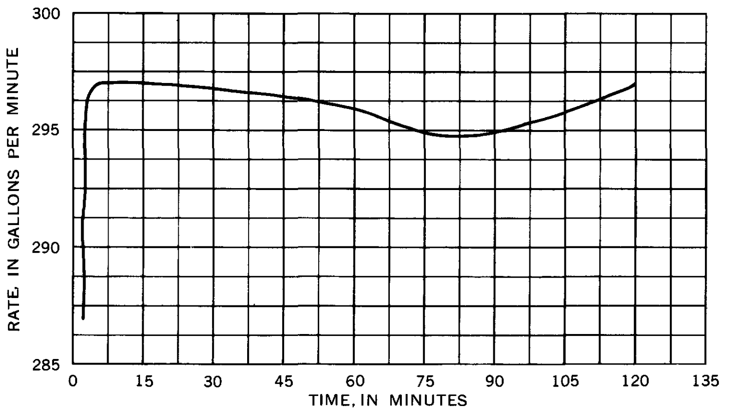
FIGURE 5.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 3. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

backwashings of the filter necessary. The testing period was to be limited to 6 hours, or less if plugging became serious before the test was completed. Short-term 6-hour tests would make possible completion of more tests with more variations in water treatment within the same testing season.

An open standpipe was added to the pipeline between the filter and the recharge well to eliminate the siphon effect and reduce filter-head loss. This procedure prevented high-turbidity water from passing through the filter.



TURBIDITY OF INJECTED WATER



RATE OF INJECTION

Calcium chloride was added to the recharge water before filtration so that the resultant water (the filter effluent contained an average of 122 ppm calcium as a result of adding calcium chloride) would have about the same percentage of monovalent cations as the native ground water. The recharge water was flocculated with alum, settled, chlorinated, and filtered as in test 2. Sodium hexametaphosphate (0.1 ppm) was added to the recharge water to keep iron in the water in solution.

Test 3 was terminated after 134 minutes of recharge at an average rate of 297 gpm. Measurements of water levels inside and outside the recharge well showed the well and aquifer were plugging after the first few minutes of injection. Some of the data collected during recharge test 3 are shown in figure 5.

The depth to water and rate of change of depth to water in observation well I and O, as compared to the hydrograph of observation well FW–SE, indicate that the permeability of the material between the recharge well and observation well FW–SE decreased rapidly (fig. 5).

After 120 minutes of discharge at 300 gpm before recharge test 3, the maximum difference in water levels in observation wells I and O was less than 0.5 foot. During recharge test 3 the difference in head between water levels in I and O after 90 minutes of recharge was about 10 feet; this difference in water levels resulted from clogging on the inner face of the recharge-well screen.

The injected water contained an average of 2.6 ppm turbidity and was about the same temperature as the ground water. These characteristics greatly reduced chances of clogging by suspended material and of release of dissolved gases. Furthermore, chances of plugging by clay dispersion and precipitated iron were greatly reduced by addition of calcium chloride and sodium hexametaphosphate to the injected water. The only major change in the manner of recharge during test 3 as compared to test 2 was opening of the pipeline between the filter and the recharge well.

During preparation for redevelopment, the container used to mix the calcium chloride solution was used to mix the sodium hexametaphosphate solution. A heavy thick white precipitate formed in the container when parts of the two solutions were mixed. Subsequent laboratory tests showed that a concentrated sodium hexametaphospate solution mixed with a dilute solution of calcium chloride would form a white precipitate, but if the amount of calcium chloride in solution was in excess of the sodium hexametaphosphate in solution, a precipitate would not form. The precipitate was soluble in dilute hydrochloric acid.

The addition of a concentrated solution of sodium hexametaphosphate to the recharge well for redevelopment could have produced a precipitate. Rather than risk further plugging of the well and aquifer by precipitation of the redevelopment chemicals, the well was acidized (Sniegocki, 1963b).

At the conclusion of test 3 the specific capacity of the recharge well was 12 gpm per ft of drawdown as compared to a pretest value of 31. After redevelopment with acid, the specific capacity of the recharge well was 25 gpm per ft of drawdown.

Later recharge tests indicated that plugging during test 3 was not caused by precipitates but was caused by air entrainment when air was allowed to enter the recharge system through the standpipe installed in the pipeline between the filter and the recharge well.

TEST 4

Recharge test 4 was made under conditions similar to those used in test 3. Because calcium chloride and sodium hexametaphosphate

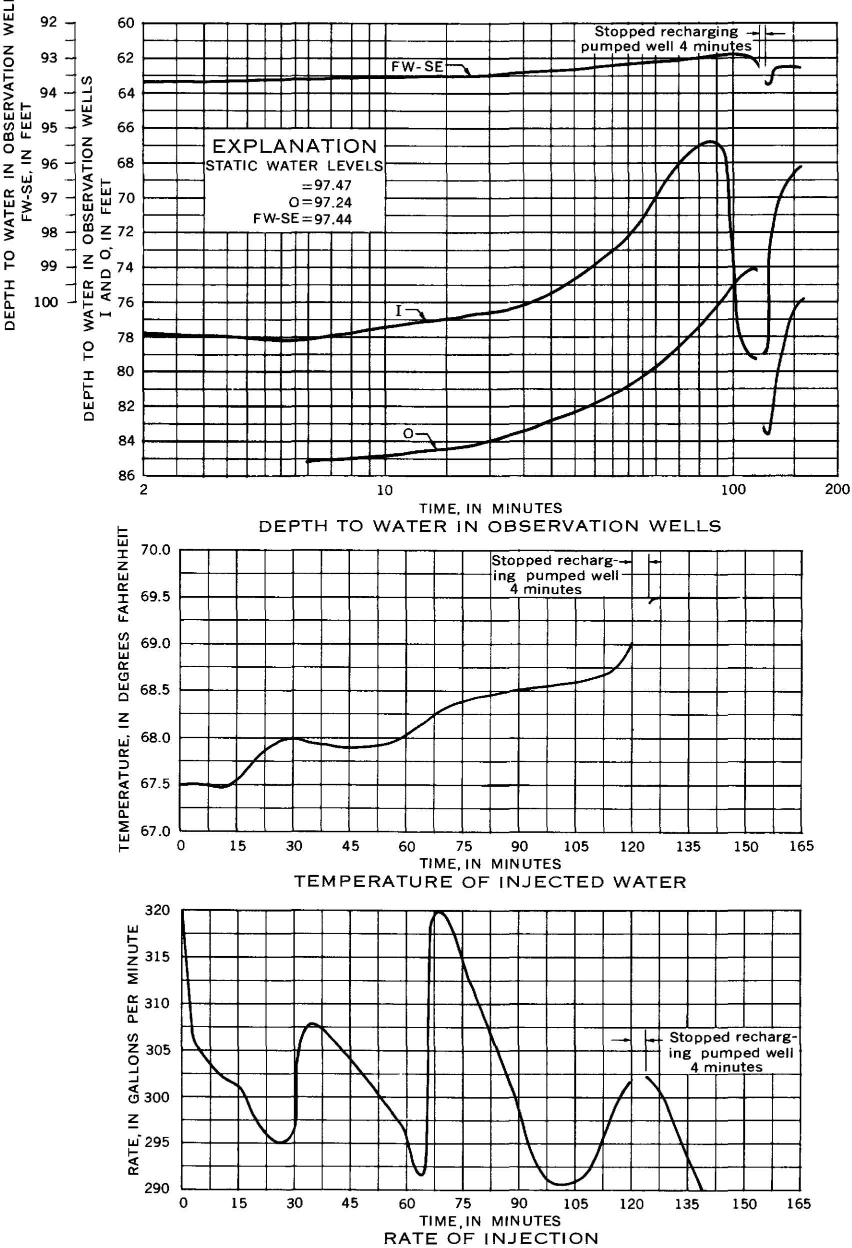


Figure 6.—Depth to water in observation wells, temperature of the injected water, and injection rate during recharge test 4. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

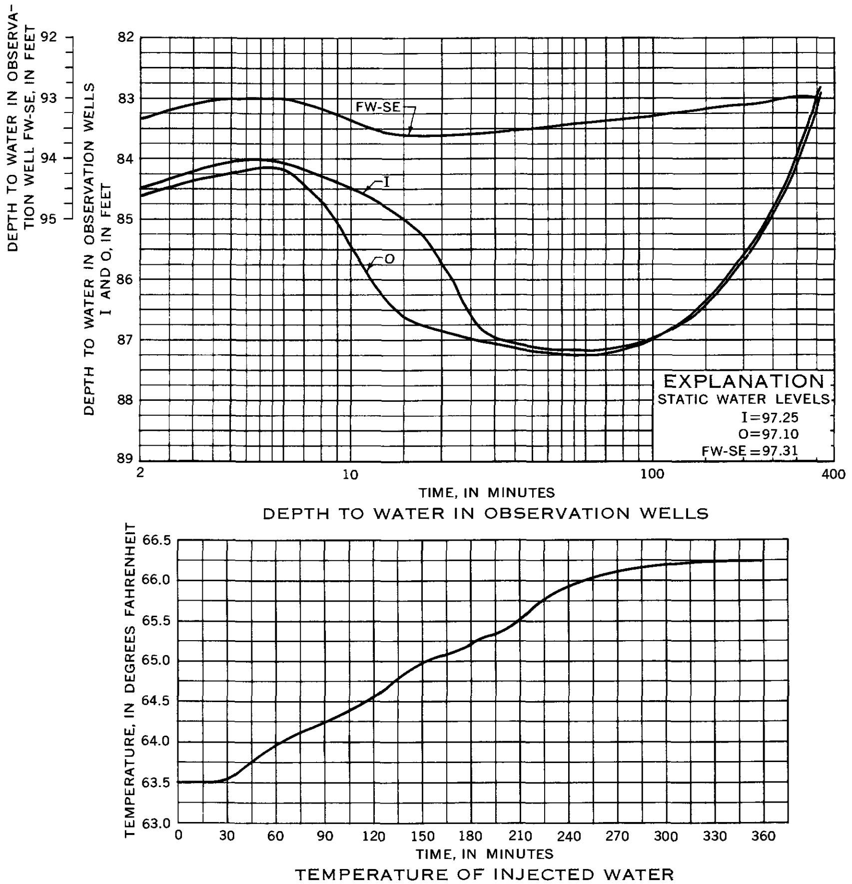
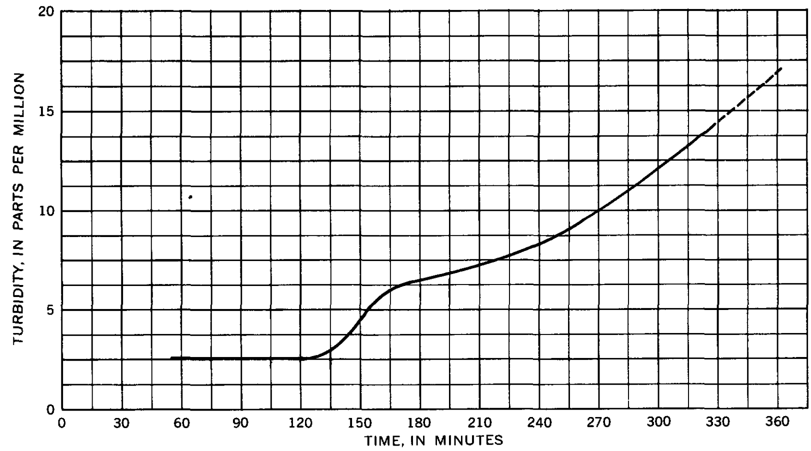


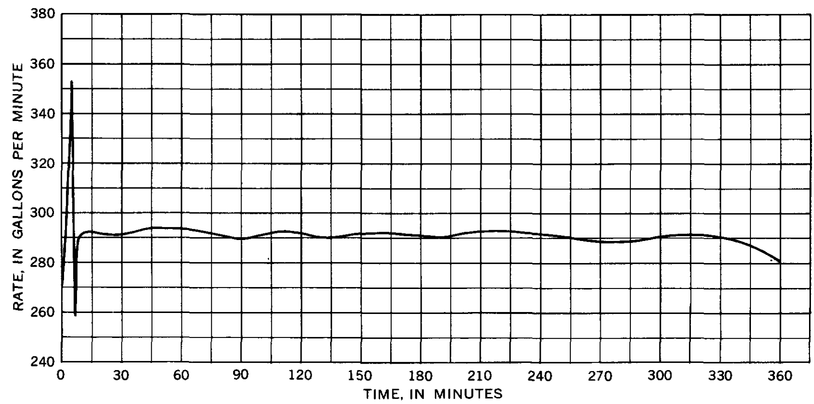
FIGURE 7.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 5. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

added to the injected water during test 3 may have contributed to well clogging, the chemicals were not added to the recharge water in this test.

Some of the data collected during test 4 are shown in figure 6. The difference in head between water levels in observation wells I and O was as much as 10 feet under recharge conditions. During the decay of the cone of elevation (refluence) after injection was stopped, the head difference was only about 0.2 foot. The air plugging on the inner face of the screen dissipated immediately when recharge was stopped. Air bubbles entrained in the recharge water could be trapped against the inner face of the screen but would rise to the surface of the water in the well when recharge stopped, and air was the only addition to the injected water common to tests 3 and 4. Therefore, air entrain-



TURBIDITY OF INJECTED WATER



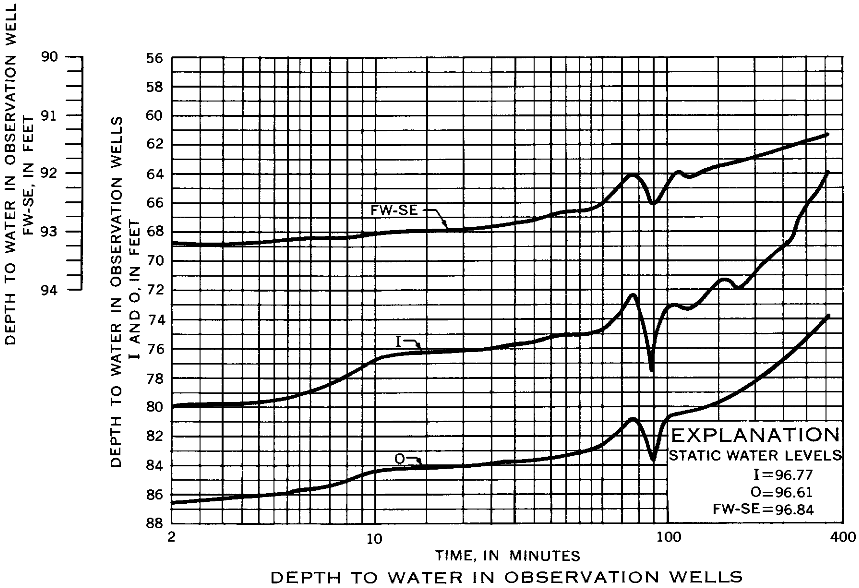
RATE OF INJECTION

ment was the major cause of clogging during test 4. Plugging by air entrainment has been discussed in detail in earlier chapters of this series (Sniegocki, 1959, 1963b).

The specific capacity of the recharge well before test 4 was 25 gpm per ft of drawdown as compared to 11 at the conclusion of the test. The recharge well was successfully redeveloped to a specific capacity of 26 gpm per ft of drawdown by application of sodium hexametaphosphate and calcium chloride to the well. A detailed discussion of redevelopment procedures used after recharge tests was given previously (Sniegocki, 1963a).

TESTS 5–6

Recharge tests 5 and 6 were designed to study air entrainment in more detail as a cause of clogging of the well and aquifer. The opening to the atmosphere in the pipeline between the filter and the recharge well was closed during test 5 to prevent the entrance of air into



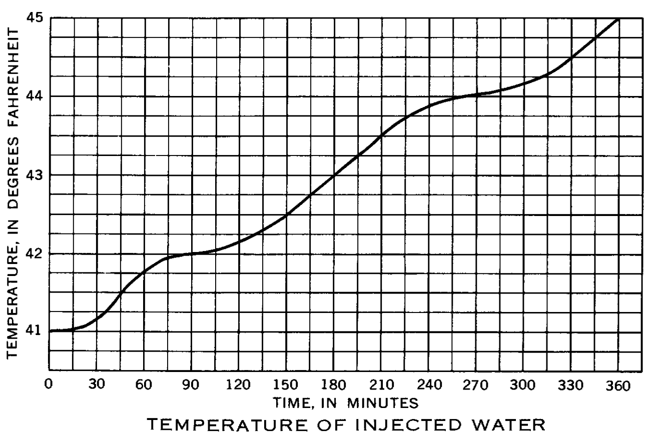
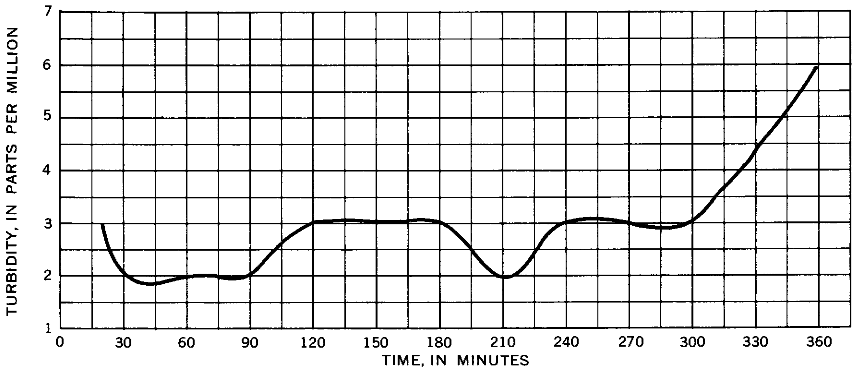
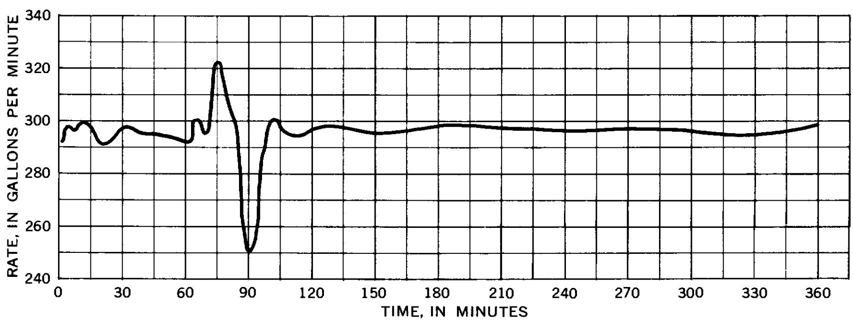


Figure 8.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 6. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

the recharge system. The filter could not be operated satisfactorily in a closed system because of the siphon effect and, therefore, was bypassed. The recharge water was flocculated, settled, and chlorinated as in tests 3 and 4. However, it was necessary to increase the alum in excess of 6 grains per gallon to obtain low-turbidity water without filtration.



TURBIDITY OF INJECTED WATER



RATE OF INJECTION

Some of the data collected during test 5 are shown in figure 7. The difference in water levels betwen observation wells I and O during test 5 became smaller when the injection rate was stabilized at about 290 gpm. The difference in the rate of change of depth to water in observation wells I and O (explaining injection-rate variations) as compared to the rate in observation well FW–SE (fig. 7) is not as great as that for the same wells in figures 5 and 6. The specific capacity of the recharge well was 26 gpm per ft of drawdown before test 5 and 25 after test completion; further evidence was thus provided of only limited plugging of the well and aquifer when air entrainment was prevented.

Recharge water was filtered during tests 3 and 4 and air, which was allowed to enter the injection line, clogged the recharge well and aquifer. Recharge water was not filtered during test 5 and air was prevented from entering the injection line; the result was little plugging. Test 6 was made with flocculated, settled, and chlorinated water. However, in an effort to duplicate the conditions of test 5, the recharge water was not filtered but the injection line was opened to the atmosphere.

756-943 O - 65 - 4

Some of the data collected during test 6 are shown in figure 8. As in tests 3 and 4, the difference in water levels in observation wells I and O was large during injection, and the specific capacity of the recharge well was reduced at least 50 percent. The average temperature of the injected water was about 22°F colder than the native ground water, and the resulting increase in viscosity was the reason for a part of the decrease in specific capacity; however, air entrainment was the major cause of clogging.

The recharge well was redeveloped to a specific capacity of 25 gpm per ft of drawdown.

TEST 7

The purpose of recharge test 7 was to determine whether the calcium chloride used in redevelopment of the recharge well before test 5 was responsible for the successful results observed during test 5. Calcium chloride was not used in the redevelopment of the recharge well after test 6. The recharge water was flocculated, settled, and chlorinated, but not filtered. Some of the data collected during test 7 are shown in figure 9. During test 7 the buildup in water level in observation well I was 12.76 feet after 6 hours of injection at an average rate of 305 gpm (fig. 9). During test 1 the buildup in water level in the recharge well was 16.65 feet at the end of 6 hours of injection of ground water at an average rate of 512 gpm. The buildup of water level in the recharge well during tests 1 and 7 was about the same, if a proportional adjustment for injection-rate differences is applied. Because the water levels in observation wells I and O were about the same throughout test 7, they indicated little or no plugging on the inner face of the recharge-well screen. Furthermore, the rate of change of buildup of the hydrographs for wells I and O did not increase until after about 200 minutes of recharge. Recharge test 7 was considered successful because plugging of the recharge well and aquifer was very slight.

No special redevelopment of the recharge well was required after test 7. The well was pumped at maximum capacity, about 800 gpm for a few minutes. The initially recovered water was greenish brown and turbid, contained moderate quantities of entrained air, and had a foul odor, but it was clear and odorless after about 2 minutes of pumping. The discharge rate was readjusted to about 425 gpm and pumping was continued for about 15 hours. After approximately a 24-hour recovery period, a specific-capacity test showed that the yield of the recharge well was 30 gpm per ft of drawdown.

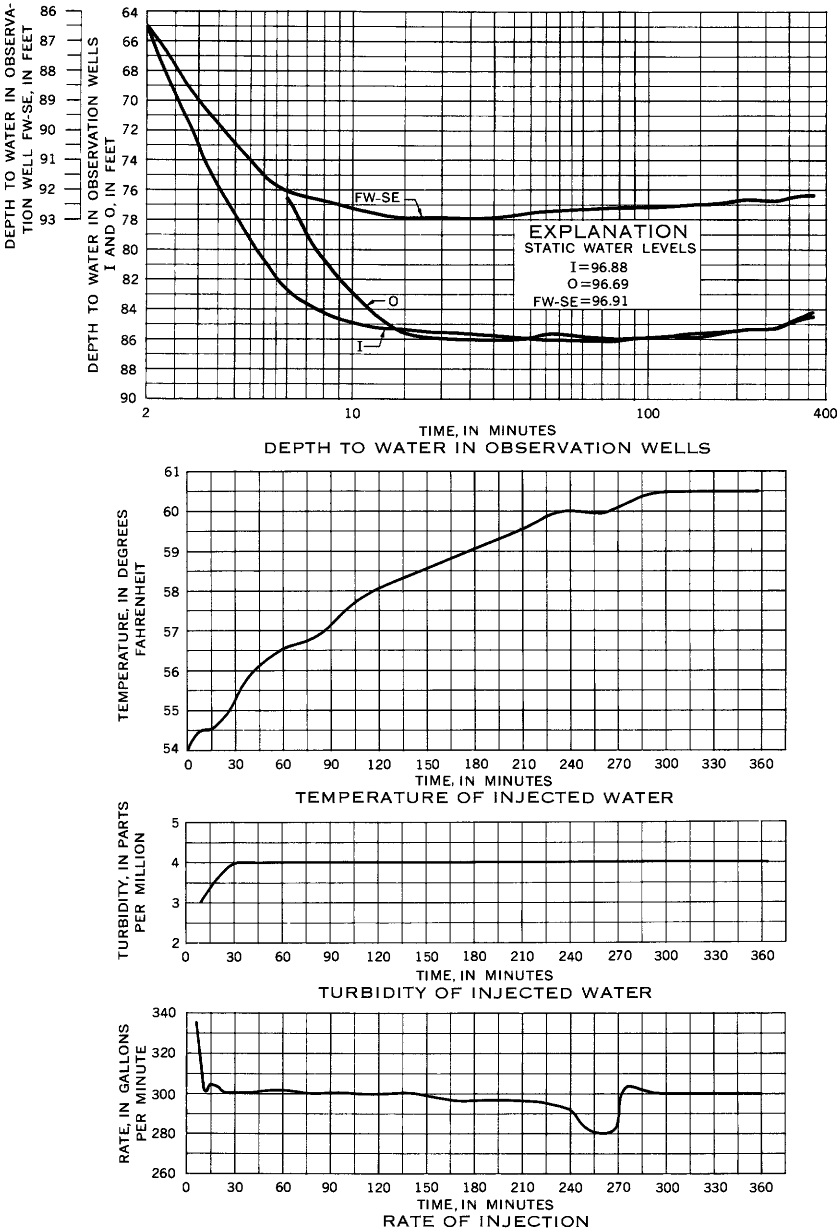


FIGURE 9.—Depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 7. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

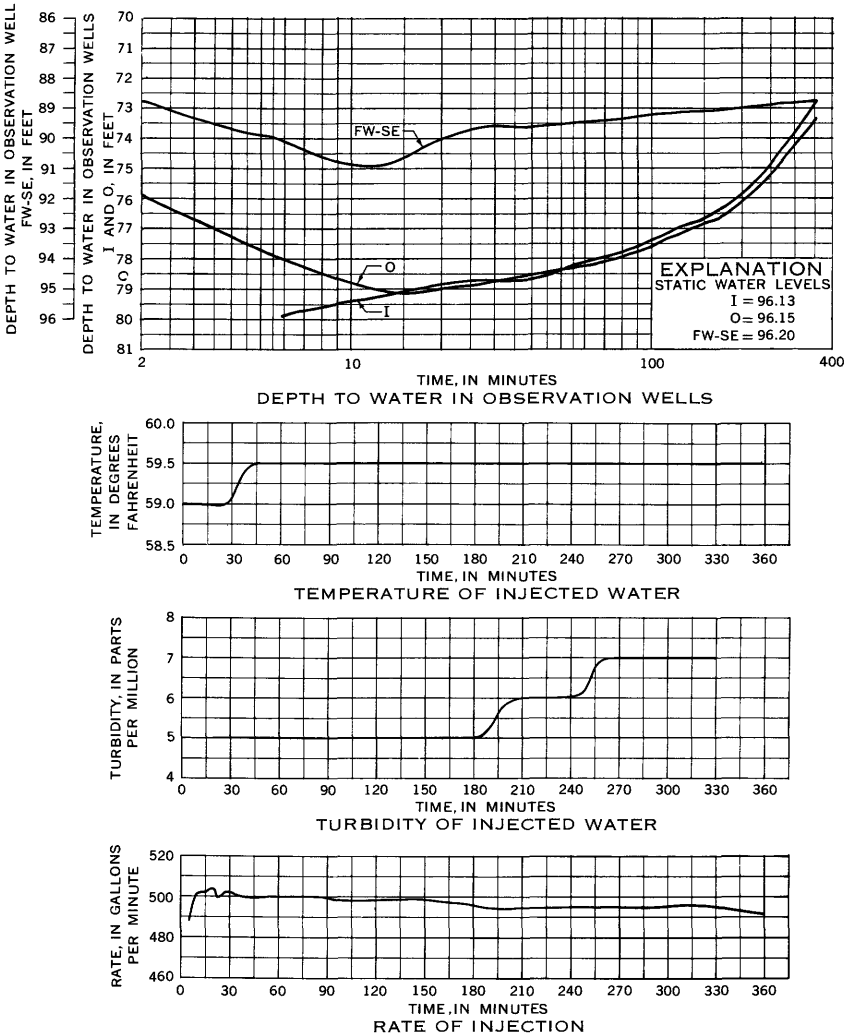


FIGURE 10.—Depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 8. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

TEST 8

If the amount of water placed into storage in an aquifer by recharge through a well is increased per unit period of injection, the cost of the operation per unit quantity placed in storage will decrease. Little or no plugging was observed in test 7, during which recharging was at an average rate of 305 gpm for 6 hours. Therefore, water treatment and the testing procedures used during test 8 were the same as those used during test 7, except that the rate of injection was increased to about 500 gpm.

Some of the data collected during test 8 are shown in figure 10. The rate of change in the water levels in observation wells I and O indicated little plugging during the first 100 minutes of recharge (fig. 10). The hydrographs are hydraulically comparable to those in figure 9 for wells I and O when a proportional adjustment for the difference in injection rate is applied. The difference in water levels in wells I and O increased as the test progressed; the minor plugging that was indicated between wells I and O probably was caused by turbidity and micro-organisms in the recharge water.

Recharge test 8 was considered successful because plugging of the recharge well was slight. Increasing the average injection rate from 305 (test 7) to 496 gpm (test 8) apparently did not appreciably increase plugging.

Special redevelopment of the recharge well was not required after test 8, and the well was pumped for about 15 hours. After a period of recovery, the specific capacity of the well was 27 gpm per ft of drawdown as compared to a pretest value of 30.

TEST 9

The purpose of test 9 was to determine the plugging effect of suspended material in the injected water and the extent of redevelopment procedures necessary to make the well suitable for continued recharge.

The surface water used in this test was the remainder of water in the canal that had been flocculated with alum and settled for use in test 8. During the period between tests 8 and 9, rainfall and wind action on the flocculated water in the settling canal caused the turbidity to increase from 6 to 16 ppm. The water, unfiltered, was chlorinated and injected into the recharge well; the possibility of air entrainment was eliminated by sealing the pipeline.

Some of the data collected during test 9 are shown in figure 11. The rate of buildup of water levels in observation wells I and O (fig. 14) and the increase in difference in water levels in the two observation wells as the test progressed are indicative of plugging of the recharge well and aquifer. That the rate of buildup of water level in observation well FW–SE also was greater in this test than in most of the previous tests indicated plugging of the aquifer at a greater distance from the recharge well. However, the injected water had an average temperature of about 42°F, and corrections for water viscosity were the reason for about half of the apparent loss of aquifer permeability,

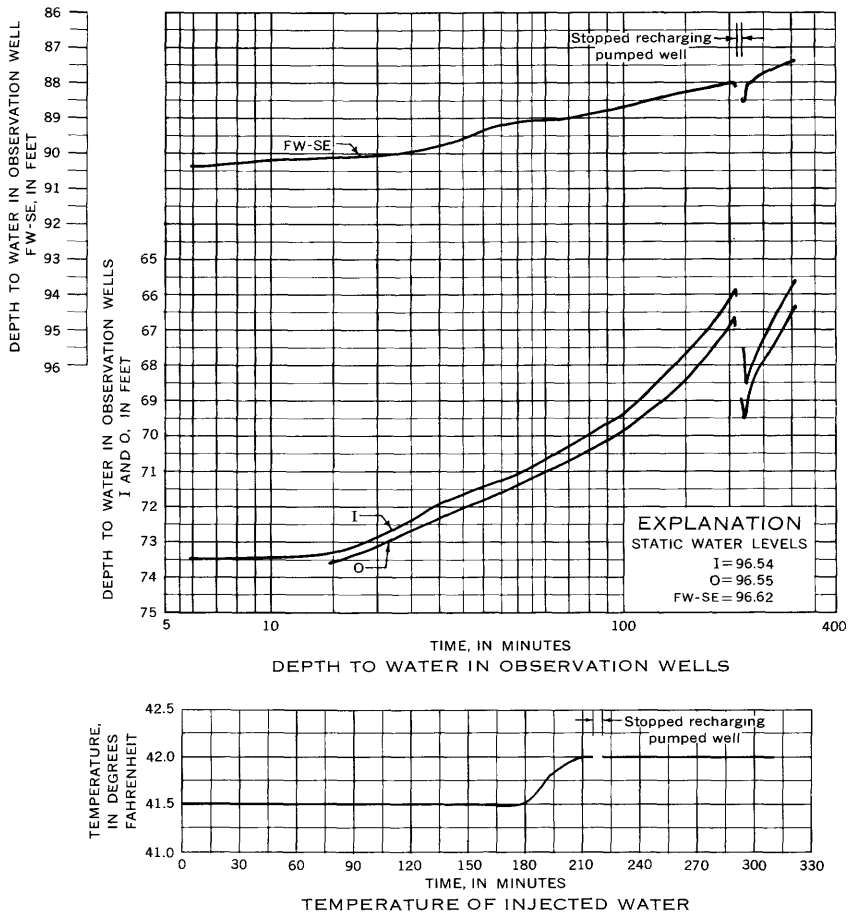
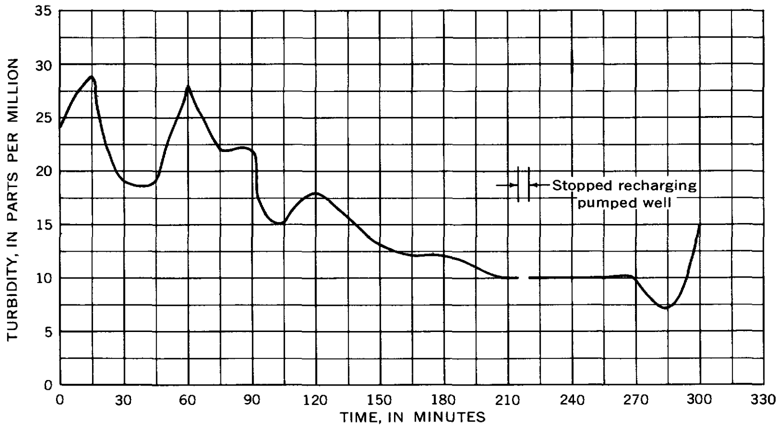


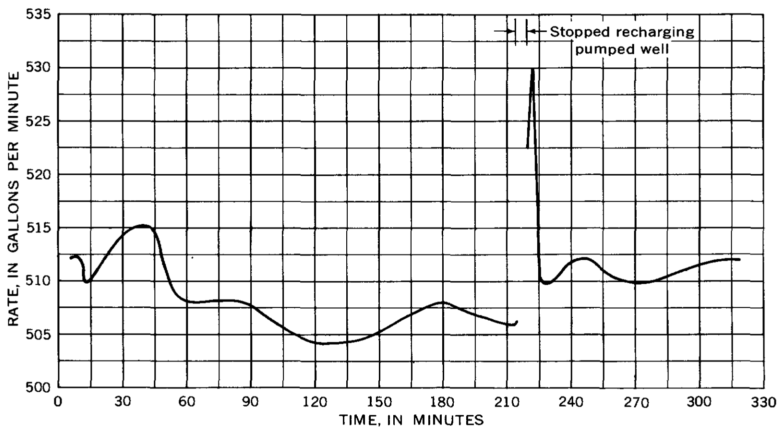
FIGURE 11.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 9. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

which was indicated by water-level changes in the observation wells. Suspended material in the recharge water probably caused most of the actual plugging.

The specific capacity of the recharge well was 27 gpm per ft of drawdown before test 9 and was 12 after the test. Surging and pumping the recharge well with the turbine pump was ineffective during the injection test (fig. 11) and after test completion in redevloping the recharge well. Use of sodium hexametaphosphate as a redevelopment agent was combined with surging and pumping; the specific capacity of the recharge well was thereby restored to 27 gpm per ft of drawdown.



TURBIDITY OF INJECTED WATER



RATE OF INJECTION

TEST 10

If artificial recharge through wells is to have practical value, injection should be accomplished over long periods of time even though the operation is interrupted by short backflushing intervals. Cyclic recharge (injected followed by backflushing) will not be effective unless maximum redevelopment of the well is attained during the backflushing interval and unless a high ratio of injected water to removed water is maintained during the redevlopment.

Very little plugging of the recharge well and aquifer was observed during recharge tests 5, 7, and 8. For these tests the injected water was flocculated, settled, and chlorinated, but not filtered; water-treatment costs were thus reduced.

Tests 5, 7, and 8 were each for a 6-hour period. Test 10 was planned to incorporate, as nearly as possible, the same testing conditions and procedures as those used during tests 5, 7, and 8, except that recharge would be tried for a longer period of time.

Flocculated, settled, and chlorinated surface water was recharged, air being excluded from the injection line, at an average rate of 498 gpm during four injection periods. At the end of each injection period the recharge well was pumped at maximum capacity for 10 minutes to remove as much clogging material as possible between recharge cycles.

Some of the data collected during test 10 are shown in figure 12. The slope of the hydrographs for observation well FW–SE (fig. 12) was approximately the same in each cycle of recharge after 15 to 20 minutes of injection. The rate of buildup of the water levels in ob-

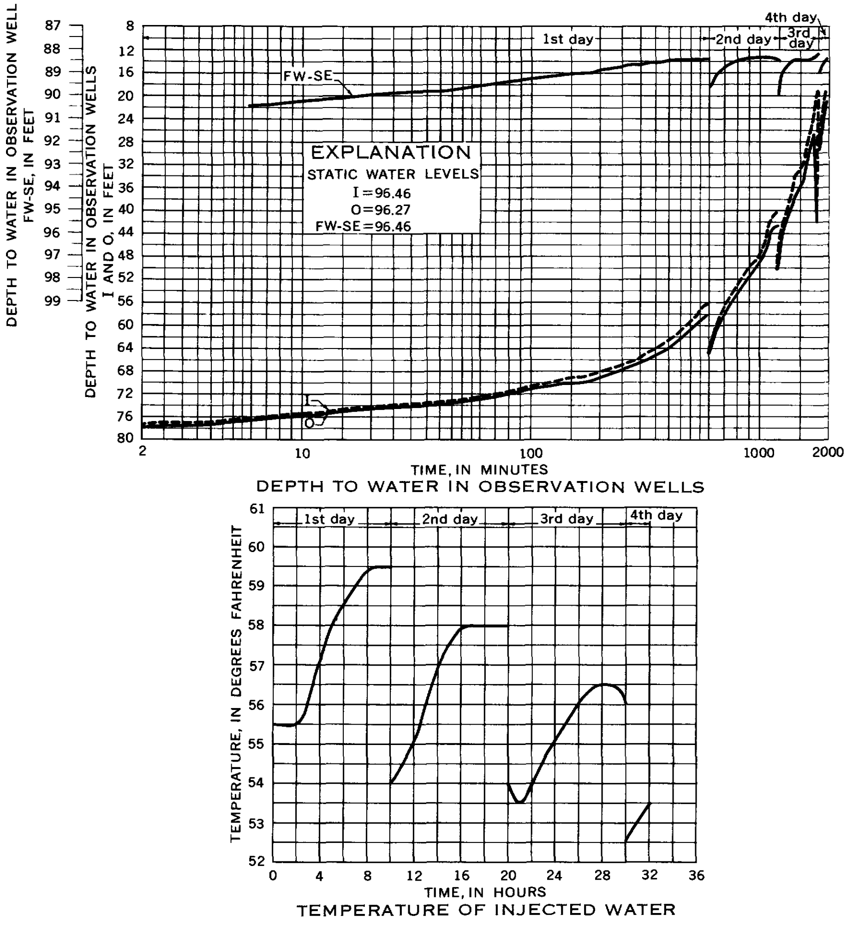
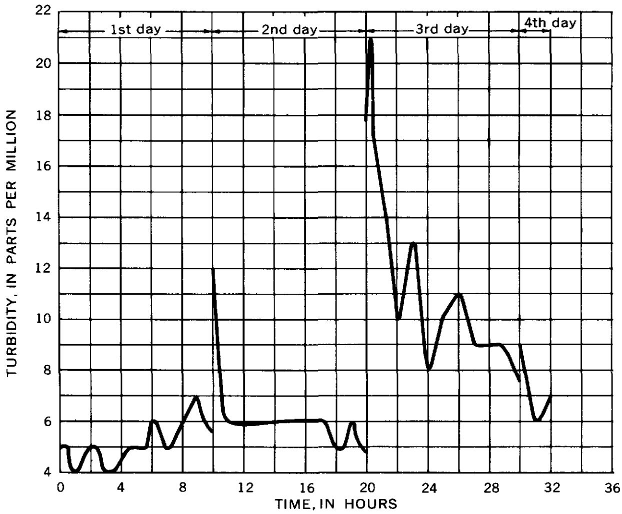
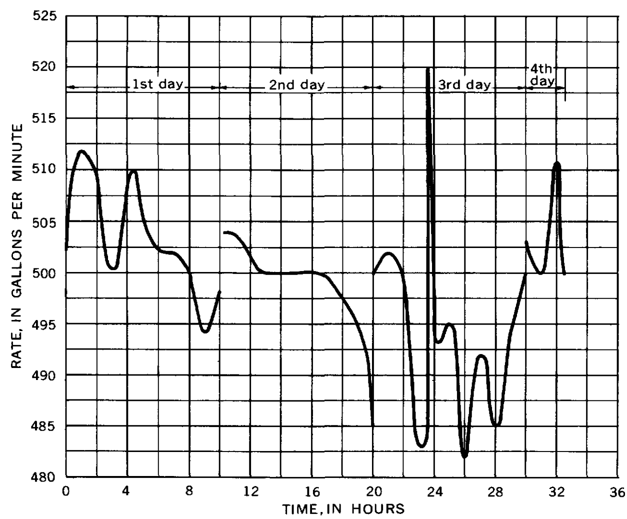


FIGURE 12.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 10. Each daily cycle is plotted immediately after the preceding cycle. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

servation wells I and O progressively increased in each cycle of recharge. Therefore, plugging of the well and aquifer was cumulative, became progressively more severe as the test continued, and mostly occurred between observation wells O and FW–SE. Most of the plugging probably was caused by suspended material in the injected water. The injection periods during tests 5, 7, and 8 were too short to show whether the permeability of the aquifer decreased as suspended material became trapped in the aquifer.



TURBIDITY OF INJECTED WATER



RATE OF INJECTION

Pumping between recharge periods did not redevelop the well and aquifer sufficiently to permit a longer period of injection. The specific capacity of the recharge well was reduced from 27 to 8 gpm per ft of drawdown. Extensive surging and pumping of the recharge well and the addition of sodium hexametaphosphate were required to redevelop the well to a specific capacity of 25 gpm per ft of drawdown. An important practical conclusion was drawn from the results of test 10. Quantitative estimates of buildup of the water level in the recharge well, based on the coefficients of transmissibility and storage of the aquifer, show that if recharge could be done continuously at 500 gpm for 200 days without plugging, the buildup of water level in the recharge well would be less than 30 feet. Thus, a gravity head of at least 65 feet would still be available for injection, and it would not be necessary to pump water into the aquifer.

However, after recharging for 150 minutes in the fourth period of injection during test 10, the depth to water in observation well I was 19.40 feet, a buildup of about 77 feet. Recharge could not have continued for more than one additional 10-hour period without pump pressure to inject the water because plugging in and near the recharge well had greatly reduced the intake specific capacity. Therefore, when plugging takes place, recharge by gravity head would be limited principally by the degree of plugging of the well and not by aquifer hydraulics.

TEST 11

Recharge test 11 was designed to determine whether the clogging effect of air entrainment was proportional to the quantity of air mixed with the recharge water. Furthermore, the aquifer was deliberately plugged by air entrainment during test 11 to determine if the air entrained in the aquifer would dissipate after a period of time when no redevelopment of the recharge well was in progress.

No equipment was readily available for metering air entering the recharge-well supply line. However, if the size of the opening that permitted air to enter the pipeline was increased, the quantity of air mixing with the recharge water presumably increased proportionately.

The injected water was flocculated with alum, settled, and chlorinated, but not filtered, as in some of the previous tests. Air was allowed to enter the supply line to the recharge well in three stages. A ½-inch valve in the supply line was opened slightly; next, it was opened completely; and, finally, a 4-inch valve was opened completely.

Some of the data collected during test 11 are shown in figure 13. No change in the shape of the hydrographs for observation wells I, O, FW–SE (fig. 13) could be correlated with changes in the size of the opening admitting air to the injected water. If a correlation existed

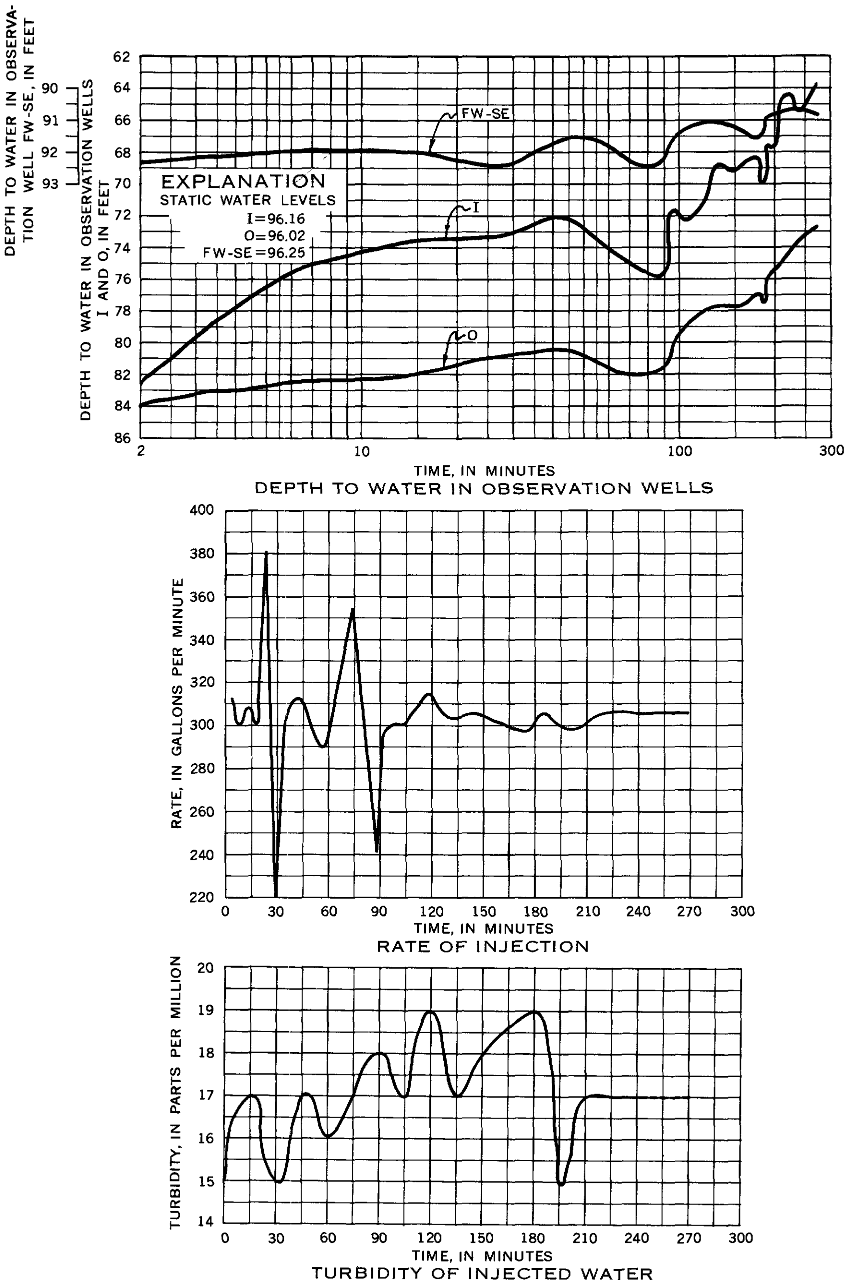


FIGURE 13.—Depth to water in observation wells, and turbidity of the injected water, and injection rate during recharge test 11. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

between the volume of air entrained and the degree of plugging, it involved quantities of air smaller than the least amount that was admitted through the ½-inch valve.

The specific capacity of the recharge well was reduced from 25 to 12 gpm per ft of drawdown as the result of plugging by air entrainment. Five short specific-capacity tests were made at intervals during a 9-week period after injection. No increase in specific capacity was observed. The maximum yield of the well without breaking pump suction was 200 to 250 gpm, whereas before injection the yield of the well was about 500 gpm.

Air bubbles trapped in the aquifer were not removed by pumping during the specific-capacity tests; the well remained unused for 9 weeks. Pumping, surging, and the application of sodium hexametaphosphate were required to redevelop the recharge well to 30 gpm per ft of drawdown.

TEST 12

Several of the previous tests were designed to establish a method of recharge in which the total buildup of water level was caused solely by hydraulic conditions of the well and aquifer and no part of the buildup was due to plugging. If recharge without plugging could be done long enough to establish approximate hydraulic equilibrium in the aquifer, the various suspected plugging factors could be added singly or in combination. It should then be possible to evaluate the magnitude of the effect of the plugging factors and to determine methods to eliminate or alleviate them in the most economical and practical manner. Test 12 was designed as a further attempt to establish a schedule of recharge operations in which injection could be done without plugging.

Water-treatment procedures were refined to provide a recharge supply of water of the best physical quality possible. Copper sulfate was applied to the raw surface water to reduce the number of microorganisms in the water. The amount of alum applied to the water for flocculation was reduced, and the rate of application was more rigidly controlled than in previous tests. The water was chlorinated and filtered into a large open tank. By moving water from the tank into the recharge well, siphon action on the filter was eliminated.

Some of the data collected during test 12 are shown in figure 14. Refining water-treatment procedures resulted in water having very low turbidity and a low micro-organism count. Water was injected at an average rate of 502 gpm for a 6-hour period. The specific capacity of the recharge well increased from a pretest value of 30 gpm per ft of drawdown to a post-test value of 33. A part of the increase in specific capacity was caused by injecting water that had a lower viscosity than the native ground water.

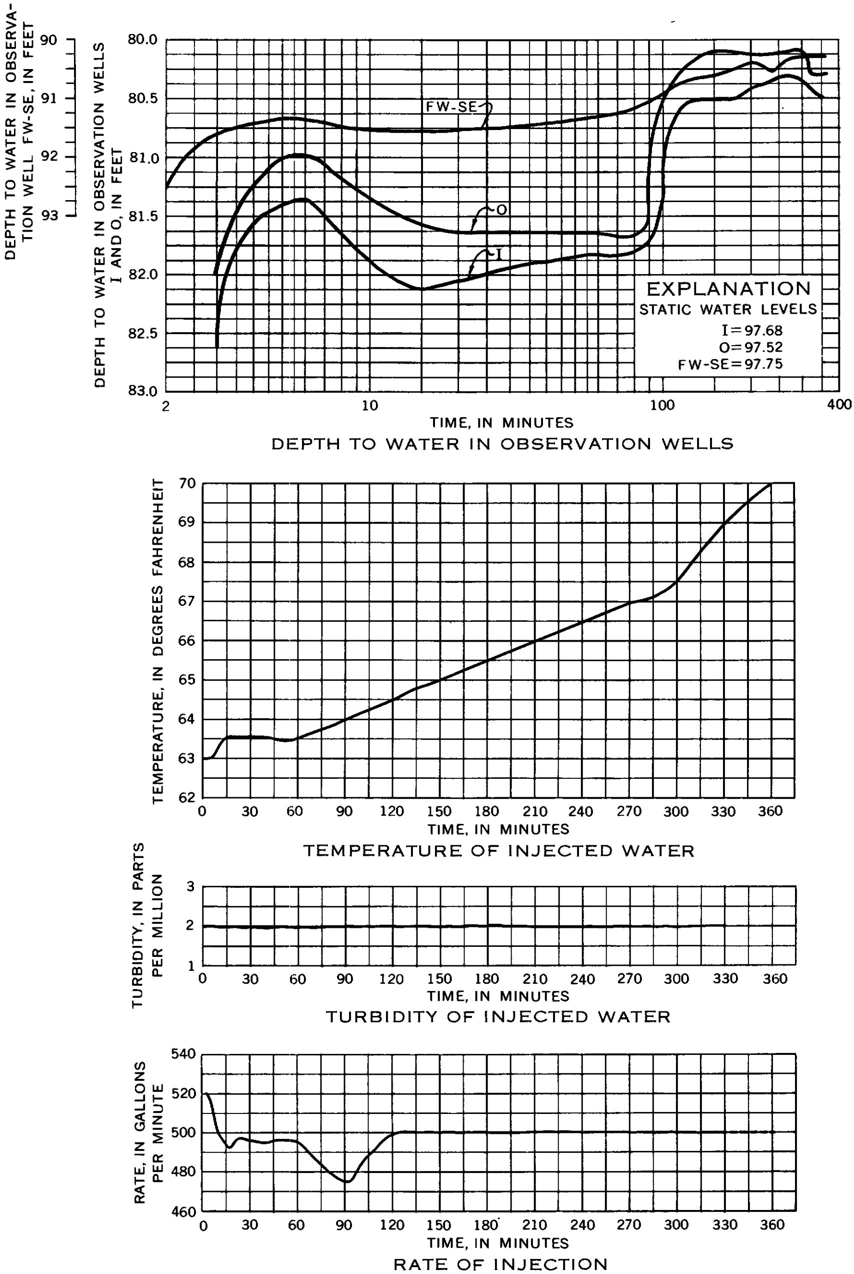


FIGURE 14.—Depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 12. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

The water level in observation well I was below that of observation well O during test 12 (fig. 14)—the reverse of what it should have been under injection conditions. Apparently, well I had become slightly clogged and was registering lagging and false water levels. During the period of recharge from 15 to 60 minutes, when the injection rate was fairly stable, the difference in water levels between wells I and O became less (fig. 14); this decrease indicated a lagging water level in well I. After 90 minutes of recharge the injection rate was increased from 475 to 500 gpm, and the difference in water levels in wells I and O increased. As recharge continued from 90 minutes to the end of the test, the difference in water levels in wells I and O again became less. When observation well I was pulled from the recharge well at a later date, the rust-encrusted slotted part of the pipe proved to be the cause of the lagging water levels.

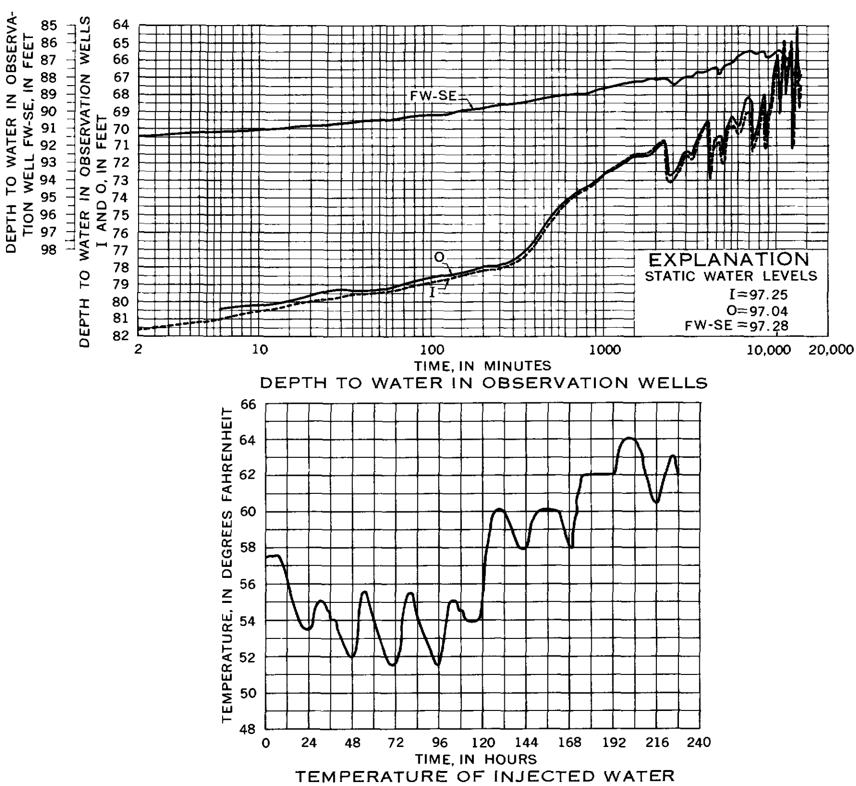
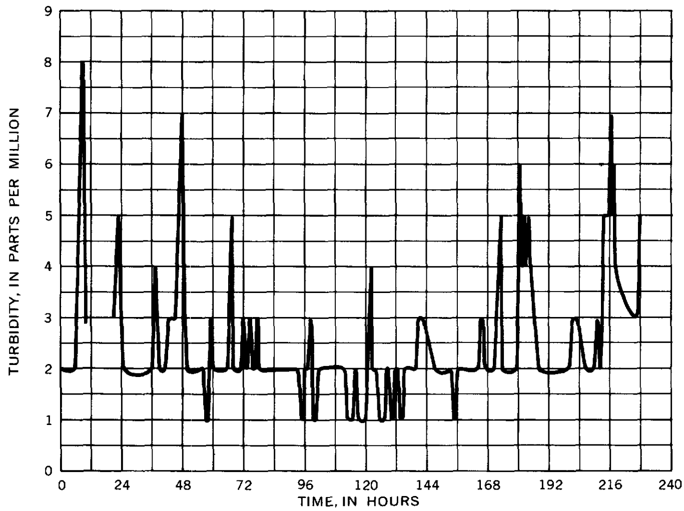


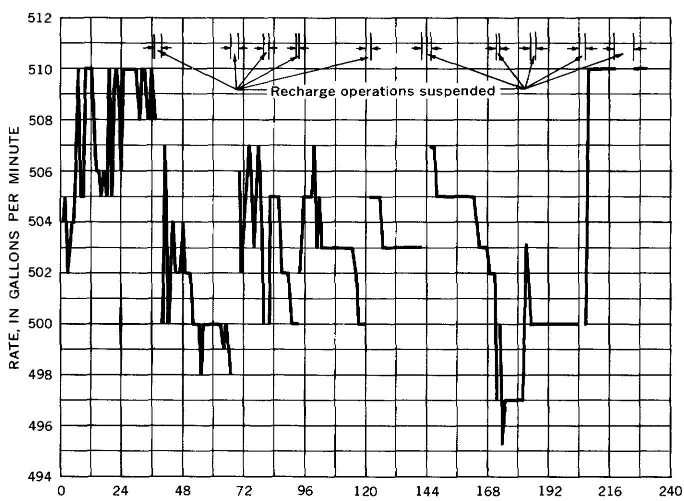
FIGURE 15.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 13. I, inside of recharge well; O, immediately outside of recharge well; FW-SE, 5 feet from recharge well.

TEST 13

The results of recharge test 12 were the most favorable of the test series completed at the time. Test 13 was designed to duplicate test 12 as nearly as possible, except that injection was planned for more than 6 hours but not to exceed 20 days. The injected water was treated with copper sulfate, flocculated with alum, settled, chlorinated, and filtered in an attempt to duplicate the water-treatment procedures used in test 12. With the exception of the temperature of the injected



TURBIDITY OF INJECTED WATER



RATE OF INJECTION

water, which averaged 65.7°F during test 12 and 57.1°F during test 13, the physical and chemical qualities of the water injected during the two tests were similar.

Some of the data collected during recharge test 13 are shown in figure 15. Slightly more than 6 million gallons of water was injected at an average rate of 505 gpm in about 12,000 minutes. Recharge operations were suspended for short periods during the test to permit backflushing of the rapid-sand filter. The specific capacity of the well was lowered from 33 gpm per ft of drawdown before the test to 18 after the test. Part of the reduction of specific capacity was caused by injecting water a few degrees colder than the native ground water. The slow plugging, shown by the progressive steepening of the hydrographs of observation wells I and O (fig. 15), apparently was partly caused by the cumulative effect of suspended material in the injected water, even though the average turbidity was only 2.4 ppm.

Part of the plugging also may have been caused by micro-organisms. The injected water contained a weighted average of 10 micro-organisms per milliliter. Throughout a large part of the test the micro-organism count was low, ranging from 5 to 15 per milliliter. However, in the latter part of the test, the count progressively increased to 92 micro-organisms per milliliter; perhaps this increase correlated with the cumulative plugging of the well.

Heavy rainfall during the latter part of the test broke up the floc and increased the turbidity of the water in the settling canal. The rapid-sand filter was not thoroughly backflushed between filter runs, and the combination of incomplete backflushing and increased filter load decreased the filter efficiency; the filter effluent had a slightly higher turbidity and a large increase in micro-organism content.

TESTS 14–17

Tests 14–17 were designed to determine the effects of recharge when the velocity of the water passing through the recharge-well screen was greatly increased. The injection rates were planned to be about 100, 300, 500, and the maximum number of gallons per minute that could be moved through the recharge system.

The best comparison of the results of each test could be made if the physical and chemical qualities of the injected water were the same in each test. Although the water-treatment equipment proved satisfactory with respect to affording a supply of excellent-quality water for short periods, it was difficult to provide duplicate types of water for extended periods. Because the ability to duplicate the type of water was limited, the water was chlorinated and filtered only; the

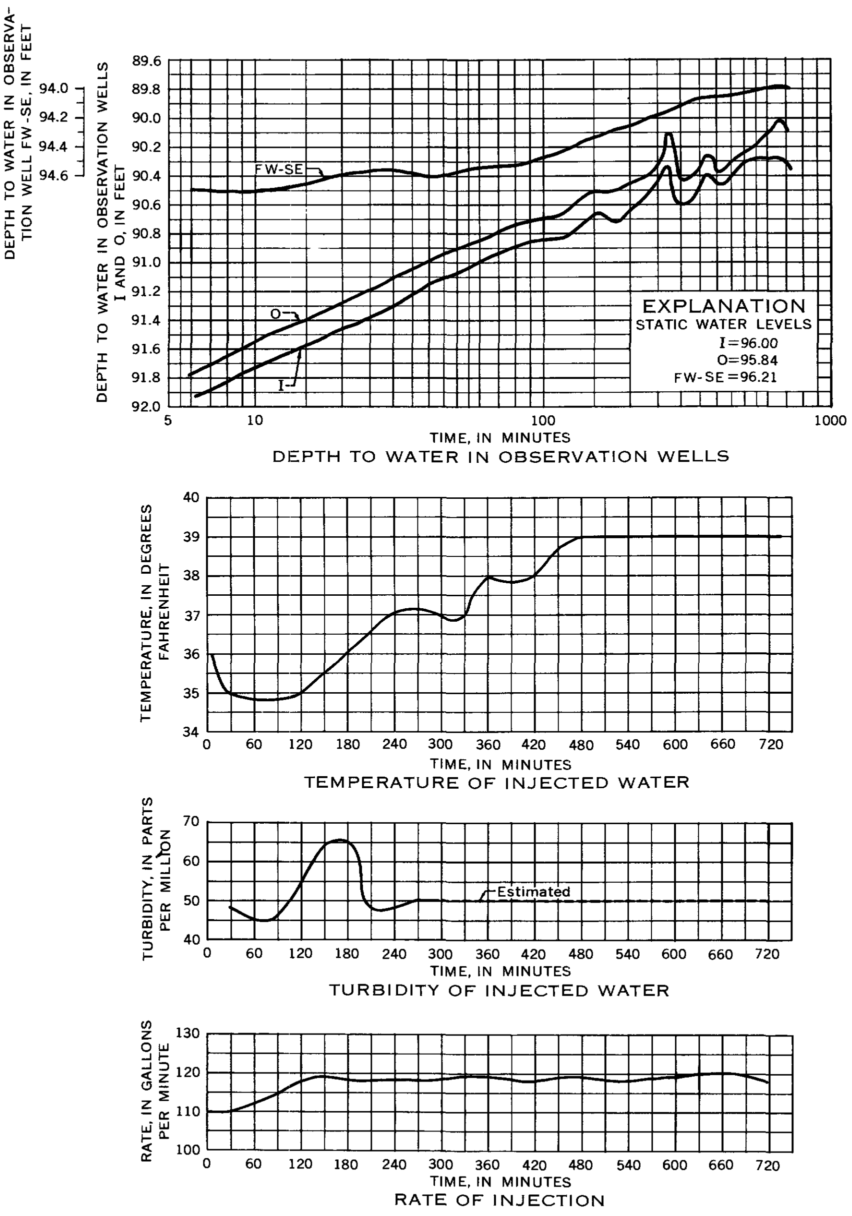
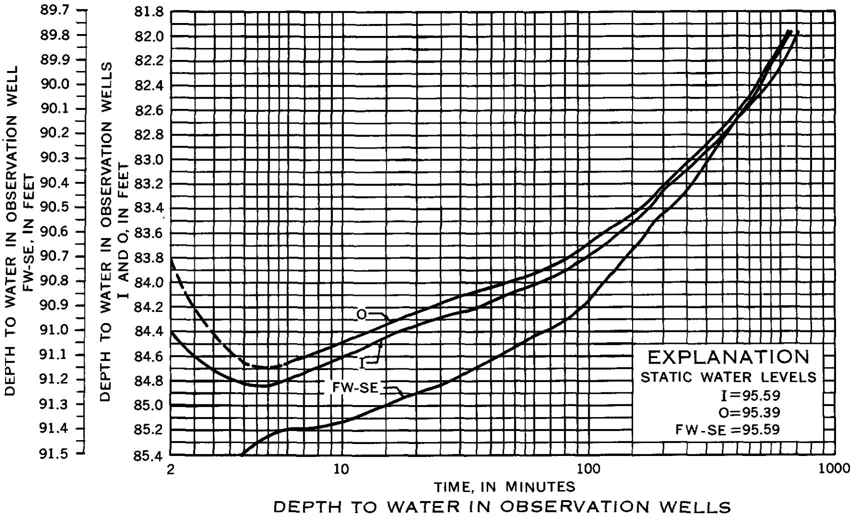


FIGURE 16.—Depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 14. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.



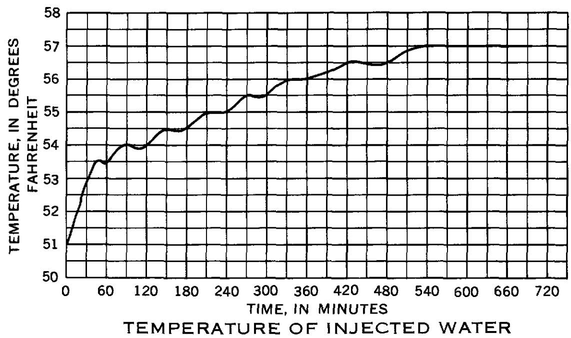
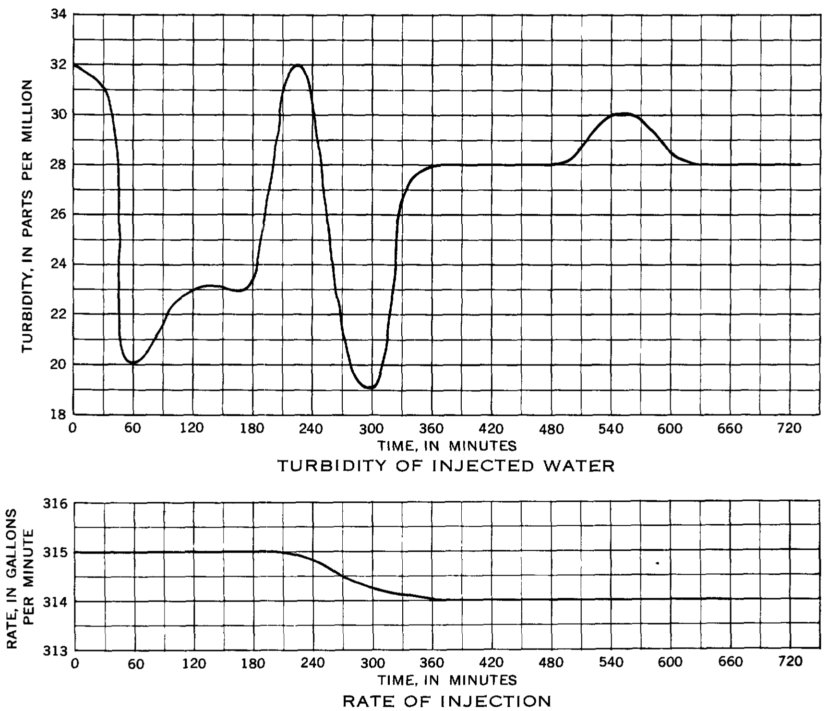


Figure 17.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 15. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.



water-treatment procedures were thus simplified and the cost of treatment reduced. Furthermore, with the exception of test 9, in all previous tests using surface water the injection supply had been flocculated with alum. Treatment with chlorination and filtration only would provide water having almost as near duplicate characteristics as could be obtained by more extensive treatment and also would provide an injection supply treated in a manner yet untried.

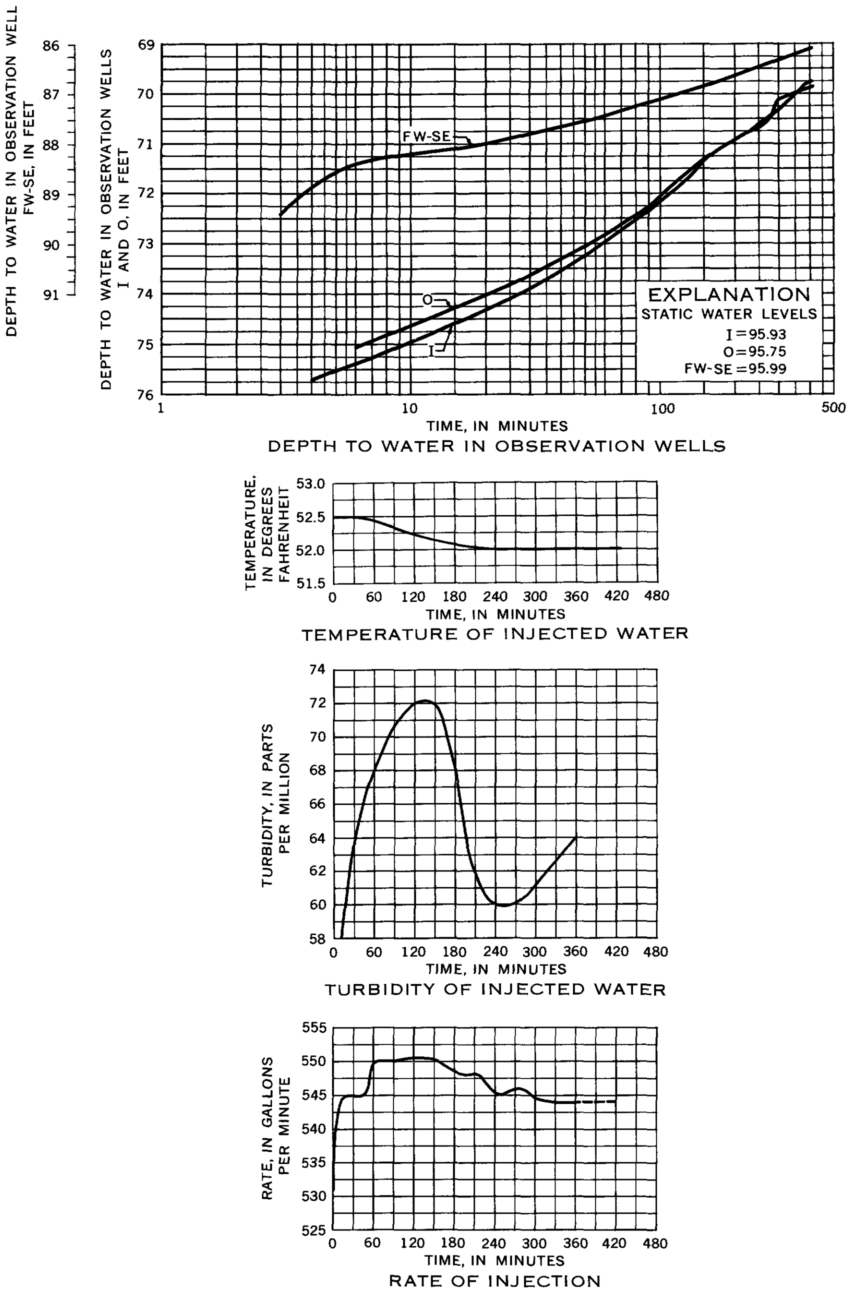


Figure 18.—Depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 16. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

Some of the data collected during tests 14–17 are shown in figures 16–19. The average temperature of the injected water was much lower than that of the native ground water during tests 14–17. (See table 1.) Adjustments to the specific capacity for changes in viscosity of the water were the reasons for a large part of the decrease in post-test specific capacities. However, the recharge well was partly plugged during each test, probably by suspended material. The changes from relatively low to high injection rates and resultant changes in velocity of water passing through the recharging-well screen had little effect on plugging.

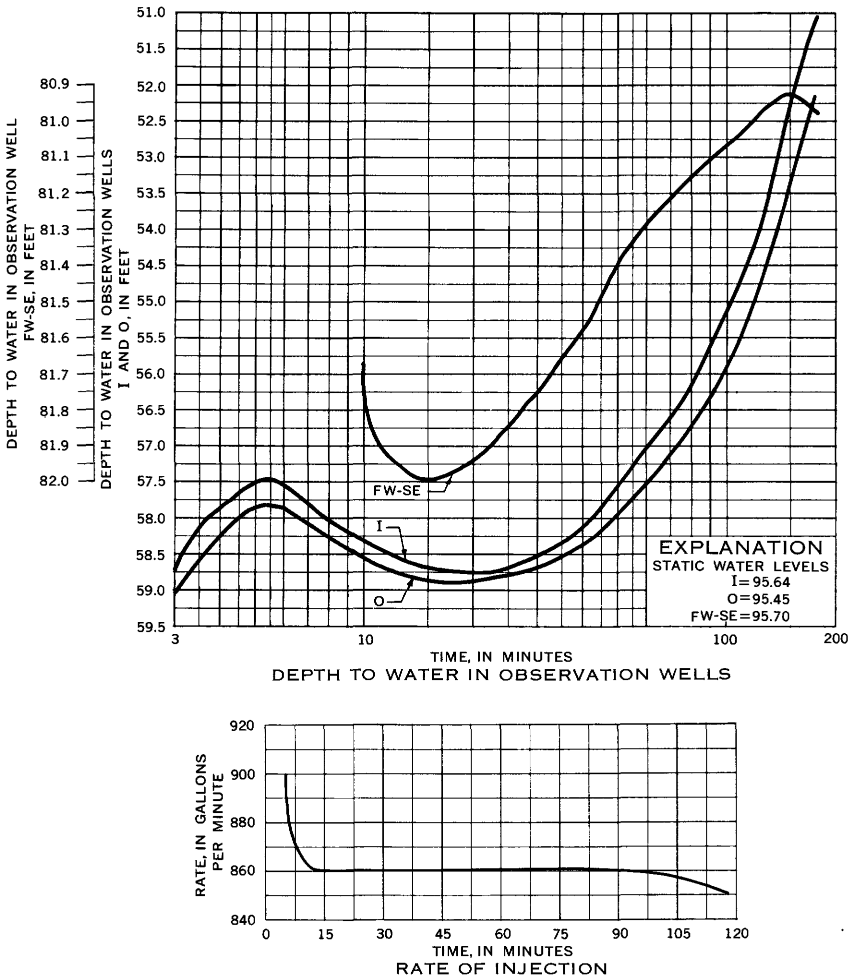
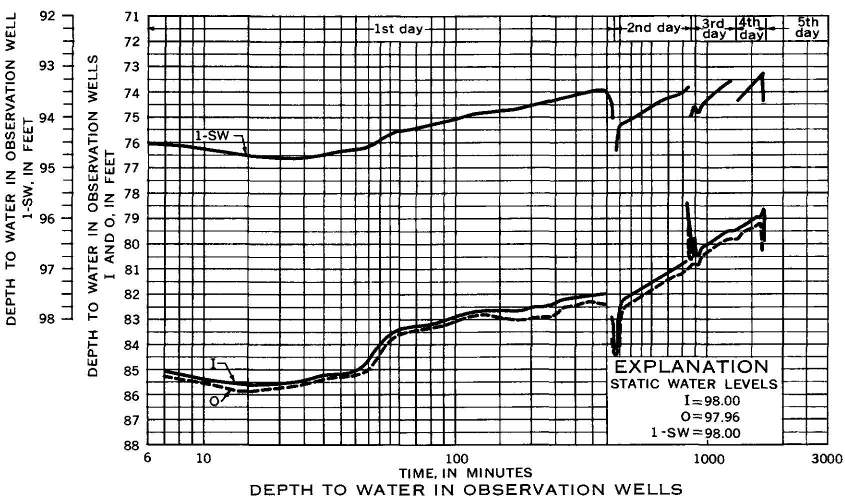


FIGURE 19.—Depth to water in observation wells, and injection rate during recharge test 17. I, inside of recharge well; O, immediately outside of recharge well; FW–SE, 5 feet from recharge well.

The filter effluent had a turbidity as low as 2 ppm when the water was flocculated with alum before filtration. During tests 14–17, when the water was chlorinated and filtered without flocculation, the lowest turbidity recorded was 19 ppm and the average was much higher in each test.

Recharge test 17 was terminated after 180 minutes of injection because a gasket in a joint in the supply line became loose from the pipe joint and lodged in the flow meter. Gaskets had not slipped during previous tests because the velocity of water flow through the supply line was much lower than during test 17.



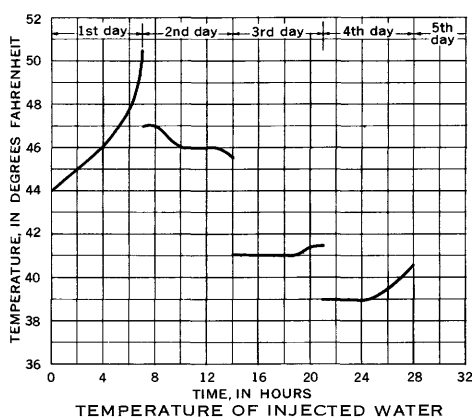


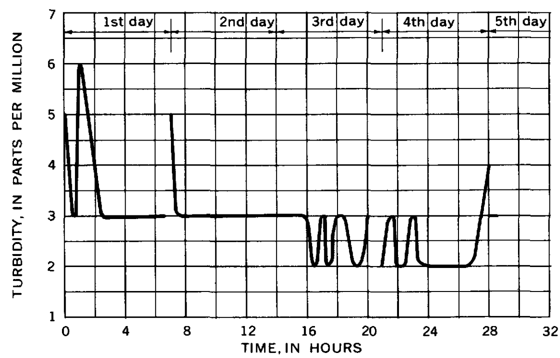
FIGURE 20.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate, during recharge test 18. I, inside of recharge well; O, immediately outside of recharge well; 1–SW, 10 feet from recharge well. Recharge operations were conducted for 7 hours each day. Each daily cycle is plotted immediately after the preceding cycle.

RECHARGE WELL 2

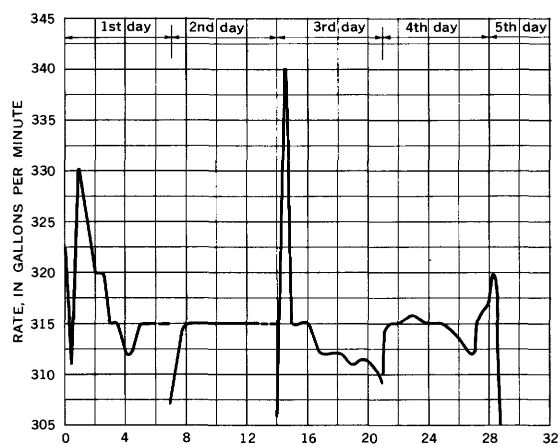
TESTS 18–21

Recharge tests 18–21 were designed principally to determine whether the sand pack and wash ring installed in recharge well 2 would permit injection for long periods of time with minimum clogging and maximum redevelopment by simple means.

The water-treatment procedures used during tests 12 and 13 provided a water supply that was injected without much plugging. Test 18 was planned for injection of water, to be treated as in tests 12 and 13, for several days to determine the injection characteristics of re-



TURBIDITY OF INJECTED WATER



RATE OF INJECTION

charge well 2 under nonplugging conditions. A major revision was made in the water-treatment equipment to ensure a supply of highly treated water for test 18. The alum feeder was moved down the canal closer to the filter; the result was a settling basin about 900 feet long as compared to a previous length of 1,800 feet. Earlier tests showed that a settling basin 900 feet long provided ample time and space for the floc to settle after the water was treated with alum. In the longer settling basin the water became turbid again after flocculation because wind and wave action broke up the floc before it could be filtered.

Some of the data collected during test 18 are shown in figure 20. The injected water was colder than the native ground water, and the viscosity difference in the two waters is the reason for the steep slope of the hydrographs shown for observation wells I and O (fig. 20). The pretest specific capacity of recharge well 2 was 27 gpm per ft of drawdown, whereas the post-test value was 17. Adjustments of these values for the increased viscosity of the injected water resulted in the lower specific capacity. The recharge well was pumped to remove the injected water from the aquifer. As soon as native ground water (65° F) replaced the injected water, the specific capacity of the recharge well was determined; it was 26 gpm per ft of drawdown.

Recharge test 19 was designed to determine whether the sand pack used in recharge well 2 (Sniegocki, Bayley, and Engler, 1961) would be effective in trapping suspended material in the injected water near the recharge-well screen and thus facilitate removal of suspended material by pumping. The recharge water was chlorinated and filtered, but not flocculated with alum; thus the injection supply had a high turbidity content.

Some of the data collected during recharge test 19 are shown in figure 21. The specific capacity of the recharge well was reduced from 26 to 20 gpm per ft of drawdown by injecting water having a higher viscosity than that of the native ground water and by plugging caused by suspended material. Suspended material in the unfiltered water that was fine enough to pass through the rapid sand filter was also fine enough to pass through the sand pack of the recharge well into the aquifer. Samples of water from an observation well approximately 40 feet from the recharge well had a turbidity of 2 ppm before test 19 was started, and as injection continued the turbidity increased to 17 ppm.

The purpose of test 20 was to determine the effectiveness of the sand pack in trapping suspended material near the recharge-well screen and the effectiveness of the wash ring as a means of cleaning the sand pack.

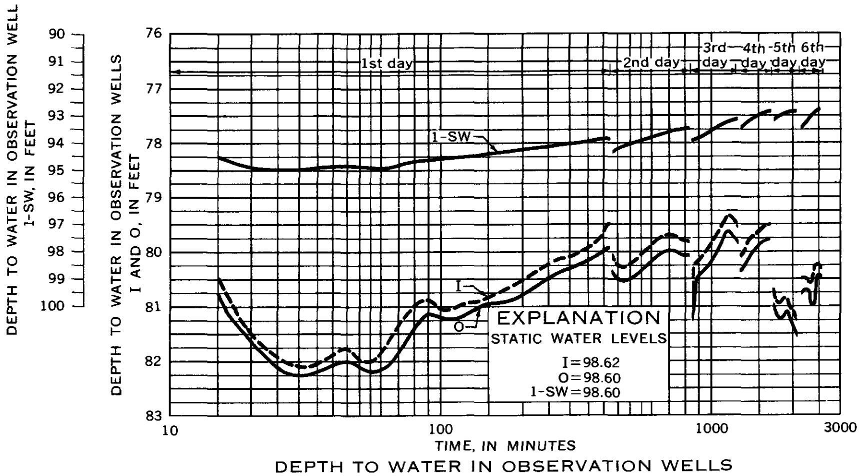
The water was chlorinated as it was siphoned from the settling canal into the recharge well through the turbine pump. The rate of injection was controlled by the butterfly valve installed at the bottom of the pump column inside the recharge well. Recharge was stopped each day, and as the well was pumped the wash ring was used to jet a stream of water against the inside of the recharge-well screen.

Some of the data collected during recharge test 20 are shown in figure 22. Each day of operation, the injection rate was set at approximately 300 gpm. As injection continued and the head inside the recharge well increased, the injection rate diminished (fig. 22). The difference in water levels between observation wells I and O became greater each day of injection and was of the magnitude observed in other tests when plugging was caused by air entrainment. The siphon was used to move water from the canal into the recharge well and air was apparently entering the injection line through an undetected pinhole.

Surging, pumping, and simple jetting with the wash ring were ineffective in maintaining the intake capacity of the recharge well during test 20 and also were ineffective in well redevelopment at the end of the test.

The effectiveness of the wash ring in redevelopment of the recharge well was further checked by test 21, in which water for injection was treated as that used in test 20 but with no possible interference from air entrainment. A pump was installed in the injection line before beginning test 21 so that water could be moved from the canal into the well without using the injection line as a siphon. Pumping against the partly opened valve at the bottom of the tailpipe created positive pressure in the injection line and prevented air entrainment.

Some of the data collected during recharge test 21 are shown in figure 23. The slope of the hydrographs of water levels in observation wells I and O became steeper after 100 minutes of recharge even though the injection rate generally was declining during the period of recharge from about 100 minutes to about 1,300 minutes (fig. 23). The difference in water levels between observation wells I and O became greater as injection continued, and after 1,000 minutes of recharge the difference was pronounced. Apparently, some suspended material in the injected water was trapped on the sand pack during the early part of the test. The sand pack became progressively less permeable as injection continued, and progressively more effective in trapping suspended material; the result was cumulative plugging of the recharge well and greater differences in water levels between observation wells I and O.



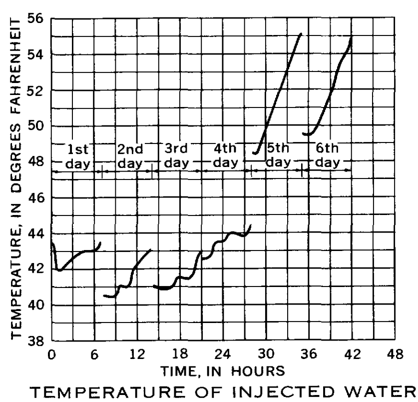
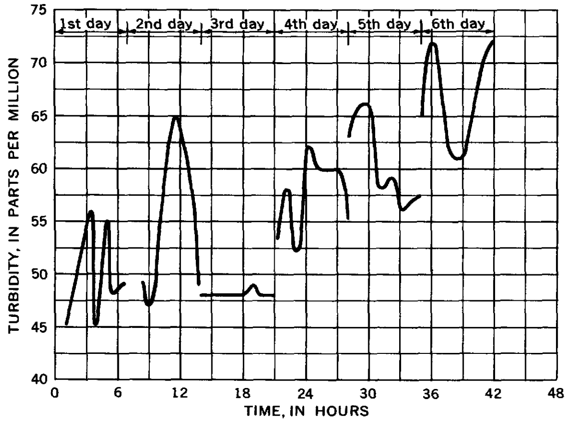
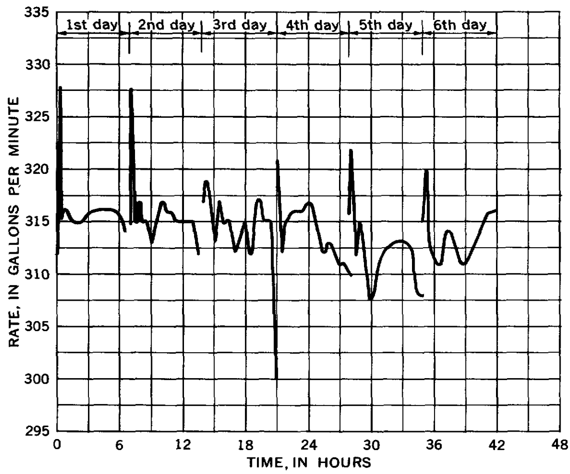


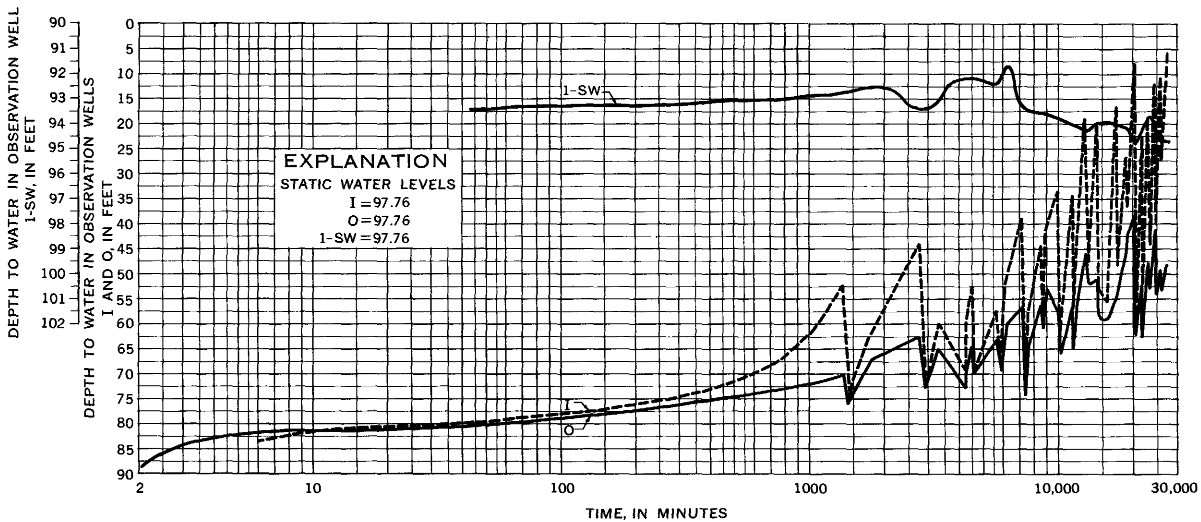
Figure 21.—Graphs (above and opposite page) showing depth to water in observation wells, temperature and turbidity of the injected water, and injection rate during recharge test 19. I, inside of recharge well; O, immediately outside of recharge well; 1–SW, 10 feet from recharge wall. Recharge operations were conducted for 7 hours each day. Each daily cycle is plotted immediately after the preceding cycle.



TURBIDITY OF INJECTED WATER



RATE OF INJECTION



DEPTH TO WATER IN OBSERVATION WELLS

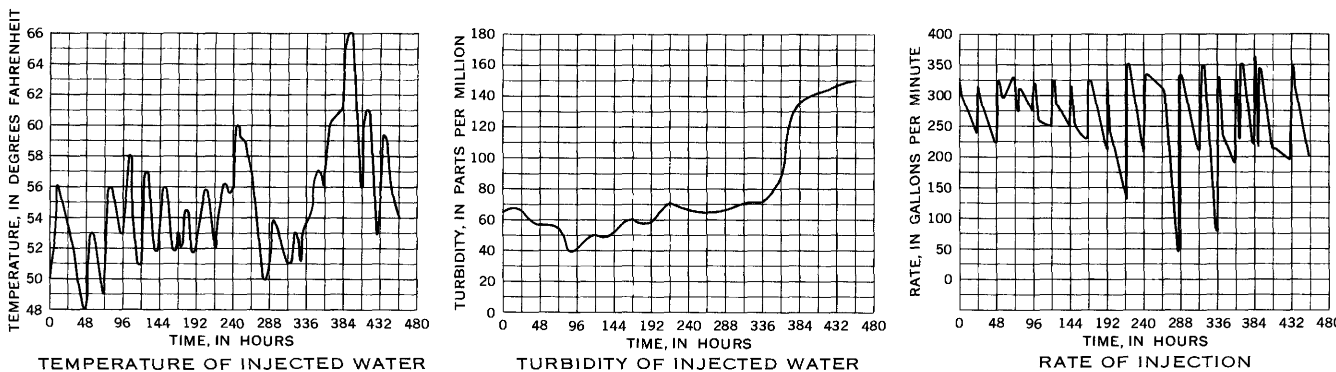


FIGURE 22.—Depth to water in observation wells (facing page), temperature and turbidity of the injected water, and injection rate during recharge test 20. I, inside of recharge well; O, immediately outside of recharge well; 1–SW, 10 feet from recharge well.

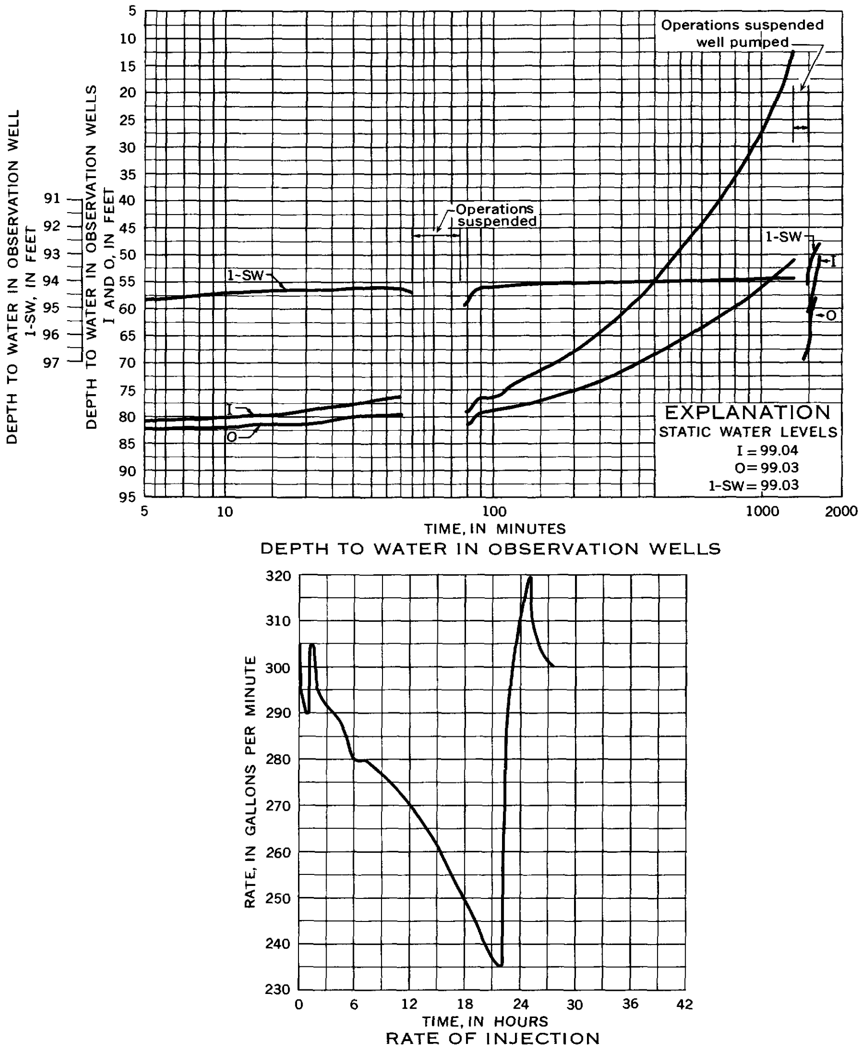


FIGURE 23.—Depth to water in observation wells and injection rate during recharge test 21; I, inside of recharge well; O, immediately outside of recharge well; 1–SW, 10 feet from recharge well.

Backflushing the recharge well and jetting water against the inside of the well screen with the wash ring was of little value in preventing cumulative clogging during recharge. The wash ring was also ineffective as an aid in redevelopment of the recharge well at the end of the test.

TEST 22

A low, as compared to a high, injection rate requires less buildup of water level in a recharge well to move water through the well screen into the aquifer; the water thus has a comparatively low velocity as it moves through the screen away from the recharge well. Consequently, with low-rate injection and maximum-rate backflushing, the backflushing-injection velocity ratio and the drawdown-buildup ratio are high and should facilitate well redevelopment after a period of recharge. Recharge test 22 was planned to determine whether low-rate injection would facilitate recharge-well redevelopment.

Surface water was chlorinated as it was pumped from the canal into the recharge well at an average injection rate of 37 gpm. Recharge was continuous except for a short period each day when the well was pumped.

Some of the data collected during test 22 are shown in figure 24. The specific capacity of the recharge well was lowered from a pretest value of 15 gpm per ft of drawdown to a post-test value of 2. Suspended material trapped on the interface of the well screen and sand pack caused a large difference in water levels between observation wells I and O in the late part of the test. Pumping each day did not redevelop the well sufficiently to permit continued recharge for a long period, even though the injection rate was low as compared to the backflushing rate.

TEST 23

Evidence from studies by Heiple (1959) showed that the turbidity of surface water may be substantially reduced by filteration at a low rate, without prior treatment, through coarse-grained material such as pea gravel. Heiple demonstrated that coarse-grained media filtration removed at least 50 percent of the total bacteria and 50 to 90 percent of the turbidity in normal waters. A coarse-grained media filter has the advantage of long-term operation without appreciable head loss and without need for cleaning; it thereby greatly reduces water-treatment costs.

Experienced gained in previous recharge tests showed that a prerequisite to successful recharge through a well at the test site was the availability of a supply of water of very low turbidity and containing few micro-organisms. Test 23 was therefore planned for recharge with water that had been filtered through coarse-grained media to determine whether an operational model of the filter described by Heiple would provide a suitable supply of injection water.

A filter tank was formed by constructing wooden walls 4 feet high, 44 feet wide, and 46 feet long (enclosing 2,024 sq ft). The walls were anchored to posts placed in the ground. The dirt bottom and wooden walls were covered with thin plastic sheeting. Perforated plastic pipe, used as an underdrain, was placed on the tank bottom and covered with 10 cubic yards of ¾-inch gravel. Approximately 90 cubic yards of ¼-inch gravel was placed over the coarse gravel to form a filter bed of about 18 inches in depth. Heiple's studies showed that maximum filter efficiency was achieved when the throughput was

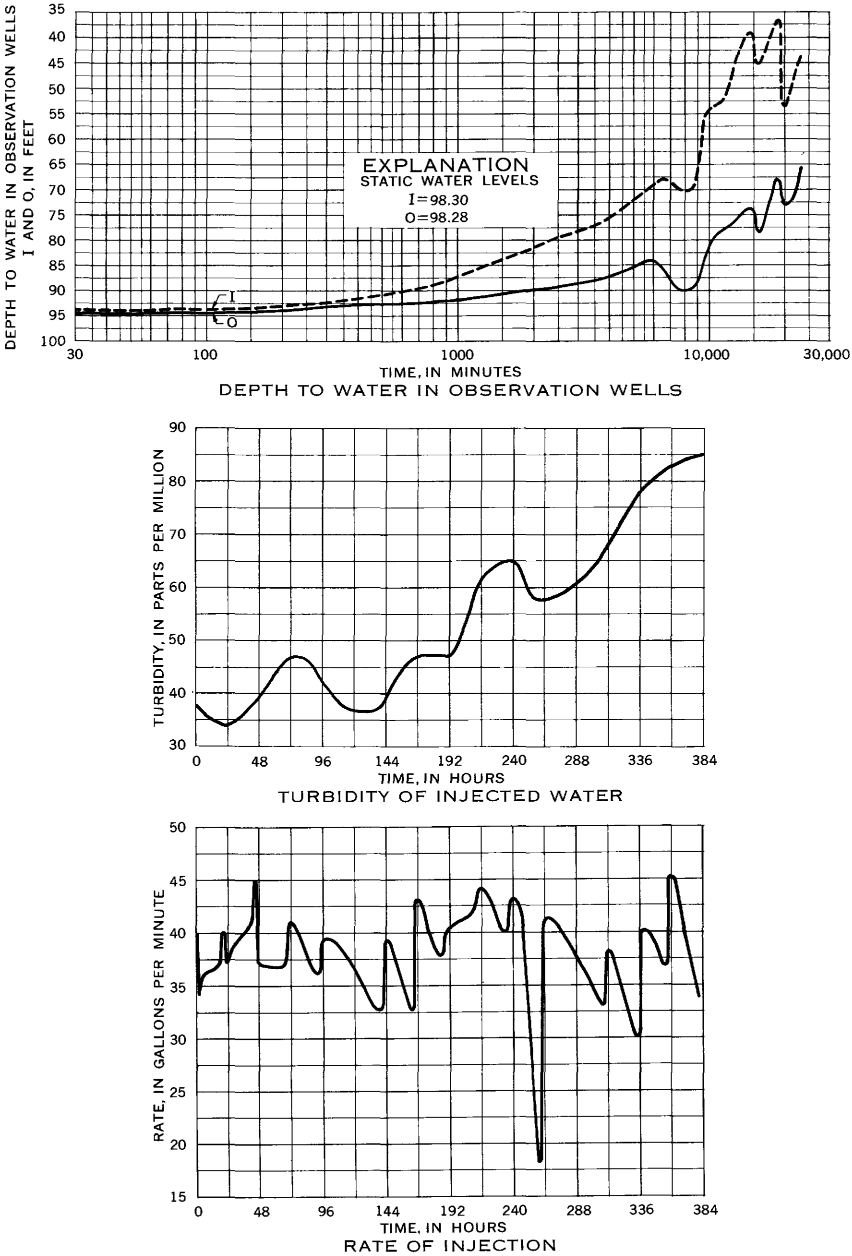


FIGURE 24.—Depth to water in observation wells, turbidity of the injected water, and injection rate during recharge test 22. I, inside of recharge well; O, immediately outside of recharge well.

limited to 0.1 gpm per square foot or less. Consequently, the filteration rate of the operational model was valved not to exceed 200 gpm.

The following table summarizes the results of turbidity measurements made on raw water and filter effluent while the coarse-grained media filter was in continuous operation.

Date	*Time*	*Filtration rate (gpm)*	*Raw-water turbidity (ppm)*	*Filter-effluen turbidity (ppm)*
1-11-61	0845	108	99	81
1-12-61	0940	106	72	69
1-13-61	0900	102	75	65
1-17-61	0835	102	59	59
1-20-61	0930	70	55	50
1-23-61	0930	68	62	50
1-31-61	0920	102	67	62

Filtration results were poor, the reduction in turbidity being only about 10 percent. Filtration tests were made at the recharge site with the same equipment utilized in the tests by Heiple. The reduction in turbidity of the filter effluent as compared to the raw water was about the same as that observed when using the operational filter. Thus, differences in the construction and size of the laboratory and field filters were not the reason for low-percentage removal of turbidity from the raw water. Consultation with Heiple established that the process causing coarse-grained media filtration to be effective is not fully understood and that physical and chemical differences in the natural waters probably caused the differences in filtration characteristics.

Some of the data collected during test 23 are shown in figure 25. The difference in water levels in observation wells I and O (fig. 25) became greater as the period of recharge lengthened. Apparently, the rate of accumulation of suspended material derived from the injected water was greater inside the recharge well than in the aquifer.

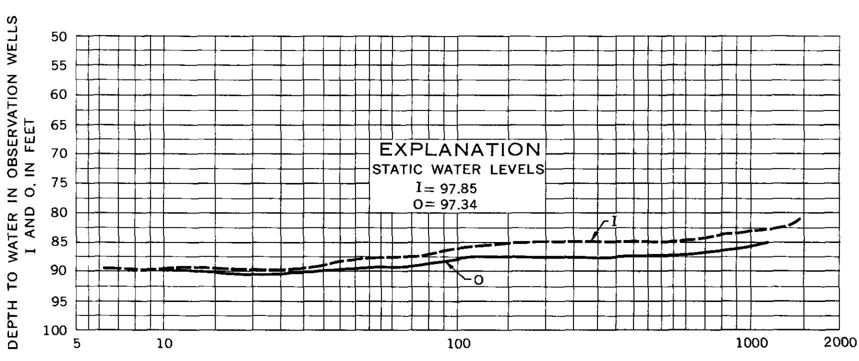


FIGURE 25.—Depth to water in observation wells during recharge test 23. I, inside of recharge well; O, immediately outside of recharge well.

The pretest specific capacity of the recharge well was 20 gpm per ft of drawdown and the post-test value was 11.

Although the coarse-grained media filter did not reduce the turbidity content of the water supply sufficiently to permit injection without substantial plugging, the test showed that the filter prevented plugging as severe as in other tests when unfiltered water was used. The filter proved to be useful also as a water conditioner, it could be used in conjunction with more extensive treatment and thus might possibly reduce treatment costs.

The turbidity content of some natural water can be substantially reduced by coarse-grained media filtration (Heiple, 1959) ; the method of filtration should therefore be tested in recharge operations for which water treatment is contemplated.

ECONOMIC ANALYSIS

A breakdown of the estimated cost per acre-foot of recharged water, based on the results of this study, is as follows: Assume that 45 acre-feet of treated water could be injected through a well into the aquifer in a 20-day period at a rate of 500 gpm, before redevelopment of the well would be necessary. The cost of the injected water, recovered for use, would be:

Operation	*Estimated cost per acre-foot of water (1962)*
Collection and conveyance of a suitable water supply for recharge	$1.90
Water-treatment equipment; installation, maintenance, and depreciation	15.00
Water treatment; operation of equipment and chemicals	20.00
Well redevelopment after recharge	1.70
Recharge well maintenance and depreciation	0.75
Pumping cost to recover injected water	10.00
Total	49.35

The water-treatment cost is approximately 70 percent of the total recharge cost. If the aquifer could be recharged through a well for long periods of time with water that had only been chlorinated, the water-treatment cost would be reduced from $35 to about $2 per acre-foot and the total recharge cost would approach economic feasibility. However, in the Grand Prairie tests, when recharging with water that received only chlorination, redevelopment costs increased greatly and the specific capacity of the well generally was not restored to the pretest value after recharge with chlorinated water. Thus, the well-replacement cost would be greater, and the combined redevelopment and well-replacement cost would likely exceed $20 per acre-foot of recharged water. Therefore, in the Grand Prairie region when recharging through wells designed similarly to those used in this study, the injected water recovered for use can be expected to cost more than $30 per acre-foot (1962 estimate).

CONCLUSIONS

Seventeen recharge tests were made with a well designed similarly to irrigation wells now in use in the Grand Prairie region, and six recharge tests were made using a well specially designed for recharge purposes. A total of slightly more than 23 million gallons of water was injected during the test series.

Little or no plugging was observed in only seven of the tests. Recharge test 12 involved the least plugging and involved injection of water that received the greatest degree of treatment. Recharge tests 5, 7, and 8 were made with water that received only flocculation and chlorination; however, the turbidity was fairly low, averaging less than 7 ppm. Recharge tests 17, 18, and 19 were made with water that received only chlorination and filtration; plugging was minor, although apparent. The turbidity of the injected water during tests 17, 18, and 19 was in excess of 50 ppm.

Plugging of the recharge well was most severe when recharge was done with highly turbid water and air was permitted to enter the injection line. Redevelopment of the recharge well was difficult after severe plugging, and the pretest specific capacity of the recharge well could not always be restored.

If recharge through wells is to be done under hydrogeologic conditions similar to those at the test site, it is recommended that the injected water be chlorinated, contain less than 5 ppm turbidity and no entrained air, be chemically compatible with the native ground water and aquifer, and have approximately the same temperature as the native ground water.

An analysis of recharge under the foregoing conditions showed that injected water recovered for use would cost more than $30 per acre-foot. The major factor determining the recharge cost is the water-treatment cost. If recharge can be accomplished with water that requires less intensive treatment or if the treatment process can be modified by using coarse-grained media filters, the cost of injected water recovered for use could be reduced to as low as $12 per acre-foot.

REFERENCES CITED

Engler, Kyle, Bayley, F. H., 3d, and Sniegocki, R. T., 1963, Studies of artificial recharge in the Grand Prairie region, Arkansas; environment and history: U.S. Geol. Survey Water-Supply Paper 1615–A, 32 p.

Heiple, L. R., 1959, Effectiveness of coarse-grained media for filtration: Am. Water Works Assoc. Jour., v. 51, no. 6, p. 749–760.

Sniegocki, R. T., 1959, Plugging by air entrainment in artificial-recharge tests: Water Well Jour., v. 13, no. 6, p. 17–18, 43–44.

——— 1963a, Geochemical aspects of artificial recharge in the Grand Prairie region, Arkansas: U.S. Geol. Survey Water-Supply Paper 1615–E, 41 p.

——— 1963b, Problems in artificial recharge through wells in the Grand Prairie region, Arkansas: U.S. Geol. Survey Water-Supply Paper 1615–F, 25 p.

——— 1964, Hydrogeology of a part of the Grand Prairie region, Arkansas: U.S. Geol. Survey Water-Supply Paper 1615–B, 72 p.

Sniegocki, R. T., Bayley, F. H., 3d, and Engler, Kyle, 1963, Equipment and controls used in studies of artificial recharge in the Grand Prairie region, Arkansas: U.S. Geol. Survey Water-Supply Paper 1615–C, 39 p.

Sniegocki, R. T., and Reed, J. E., 1963, Principles of siphons with respect to the artificial-recharge studies in the Grand Prairie region, Arkansas: U.S. Geol. Survey Water-Supply Paper 1615–D, 19 p.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground water storage: Am. Geophys. Union Trans., v. 16, p. 519–524.

U. S. GOVERNMENT PRINTING OFFICE : 1965 O - 756-943