Artificial Recharge to a Freshwater-Sensitive Brackish-Water Sand Aquifer, Norfolk, Virginia

GEOLOGICAL SURVEY PROFESSIONAL PAPER 939

Prepared in cooperation with the Department of Utilities, Norfolk, Virginia

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By DONALD L. BROWN *and* WILLIAM D. SILVEY

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ENGLISH-METRIC EQUIVALENTS

[Although the conversion factors are shown to four significant figures, the metric equivalents in the text of this paper are shown only to the number of significant figures consistent with the values of the English units]

English unit		Metric equivalent	
inch (in)	=	25.4	millimetres (mm)
foot (ft)	=	.3048	metre (m)
gallon (gal)	=	3.785	litres (l)
gallon (gal)	=	.003785	cubic metre (m^3)
million gallons (Mgal)	=	3785	cubic metres (m^3)
gallon per minute (gal/min)	=	.06309	litre per second (l/s)
gallon per minute per foot (gal $min^{-1}ft^{-1}$)	=	.207	litre per second per metre (l $s^{-1}m^{-1}$)
foot per day (ft/d)	=	.3048	metre per day (m/d)
cubic foot per day per foot ($ft^3d^{-1}ft^{-1}$)	=	.0929	cubic metre per day per metre ($m^3d^{-1}m^{-1}$)
pound per square inch (lb/in^2)	=	6.8948	kilopascals (kPa)
horsepower	=	.7457	kilowatt (kW)

ARTIFICIAL RECHARGE TO A FRESHWATER-SENSITIVE BRACKISH-WATER SAND AQUIFER, NORFOLK, VIRGINIA

By DONALD L. BROWN and WILLIAM D. SILVEY

ABSTRACT

During late 1971 and early 1972, three injection and withdrawal tests were made at the Norfolk, Va., injection site. In test 1, freshwater was injected at the rate of 400 gal/min (25 l/s). The specific capacity of the well decreased from 15.4 to 9.3 gal $min^{-1}ft^{-1}$ or 3.2 to 1.9 $ls^{-1}m^{-1}$ of drawdown at the end of 260 minutes of injection. In test 2, the initial injection rate of 400 gal/min (25 l/s) decreased to 215 gal/min (14 l/s) after 7,900 minutes of injection. The specific capacity dropped from 14.2 to 3.7 gal $min^{-1}ft^{-1}$ or 2.9 to 0.77 $ls^{-1}m^{-1}$ during the test. At the start of test 3, the aquifer accepted water at a maximum rate of 290 gal/min (18 l/s), but the injection rate decreased to 100 gal/min (6.3 l/s) within 150 minutes and continued to decrease to a low of 70 gal/min (4.4 l/s) after approximately 1,300 minutes. The specific capacity decreased from 3.7 to 0.93 gal $min^{-1}ft^{-1}$ or 0.77 to 0.19 $ls^{-1}m^{-1}$. Attempts at redevelopment of the injection well failed to improve the specific capacity.

Current-meter surveys made during injection and withdrawal pumping indicate that the reduction in flow and specific capacity were due to a uniform reduction in the hydraulic conductivity of all contributing zones in the aquifer and not to a complete shutoff of flow from selected parts of the aquifer. The hydraulic and chemical data indicate that the uniform loss of specific capacity of the contributing zones was due to dispersion of interstitial clay and that this clay would readily respond to chemical treatment for the purposes of decreasing or eliminating dispersion.

Subsequently, a pre-flush of 3,000 gal (11 m^3) of 0.2*N* calcium chloride solution was injected in front of the freshwater prior to injection test 4. The initial specific capacity was 4.3 gal $min^{-1}ft^{-1}$ or 0.89 $ls^{-1}m^{-1}$ and, by redevelopment pumping during injection, the specific capacity was improved to 5.3 gal $min^{-1}ft^{-1}$ or 1.1 $ls^{-1}m^{-1}$. After injecting 4 Mgal (million gallons) (15,100 m^3) of freshwater, an additional 3,000 gal (11 m^3) of 0.4*N* calcium chloride solution was added to the formation. A total of 20,146,100 gal (76,300 m^3) of freshwater was injected during test 4. The specific capacity remained fairly constant throughout the injection of the first 16 Mgal (60,600 m^3), indicating the stabilization of interstitial clay in the aquifer was accomplished. After 16 Mgal (60,600 m^3) had been injected, particulate clogging began occurring, and the specific capacity fell to less than 3 gal $min^{-1}ft^{-1}$ or 0.62 $ls^{-1}m^{-1}$.

Current-meter traverses made during test 4 injection showed that because of the deterioration of aquifer properties caused by tests 1, 2, and 3, the calcium chloride preferentially treated the most permeable part of the aquifer. As a result, a combination of dispersion and particulate clogging caused the lower 40 ft (12 m) of the aquifer to be plugged so that the freshwater selectively injected into the upper part of the aquifer.

As withdrawal pumping began, the lower part of the aquifer became unclogged resulting in the brackish formation water mixing with the freshwater. Only 20 percent of the volume injected during test 4 was recovered as potable freshwater. Tests 1 and 2 showed that if clogging of the screen in the injection well can be prevented, as much as 85 percent of the injected water can be recovered and will remain within the drinking-water standards of the U.S. Public Health Service (1962).

Treatment of the injection well with a clay stabilizer prior to the injection of any freshwater will minimize clogging and increase recovery of freshwater. If plugging of the screen can be prevented so that injection and withdrawal flow patterns remain similar, the storage of freshwater in a brackish-water sand aquifer is feasible.

INTRODUCTION

The water supply for the city of Norfolk, Va., comes from surface impoundments in the independent cities of Nansemond, Norfolk, and Virginia Beach. During the winter months, when water demand is low and reservoirs are full, water must be diverted from the reservoirs and allowed to escape to the ocean with the potential use of the water unfulfilled. It has been estimated (Schweitzer, oral commun., 1968) that as much as 2.5 Bgal (billion gallons) (9,460,000 m^3) of water per winter quarter could be available for use if sufficient storage areas were available.

The U.S. Geological Survey and the city of Norfolk entered into a cooperative program to determine if it would be possible to utilize the water presently flowing to waste by processing it in the treatment plants and storing it underground in aquifers containing saline water. The freshwater would then be retrieved during the summer months when peak water demands and low water levels in reservoirs place strains on the present water system.

LOCATION OF AREA

The Norfolk injection site is at Moore's Bridges Filter Plant, Norfolk, Va. (fig. 1). Excess water from the filter plant supplies the injection project. The water is taken from the treatment system after it has been chlorinated, settled, and filtered, but prior to the final chlorination and liming.

PREVIOUS INVESTIGATIONS

The first attempt at artificial recharge of freshwater into brackish-water aquifers in the Coastal Plain of Virginia was conducted by D. J. Cederstrom (Cederstrom, 1957) in 1946 at Camp Peary. During that experiment, water was injected into a brackish-water aquifer over a period of 85 days. The well into which the water was injected had screens in the intervals of 430 to 440 ft (131 to 134 m) and 450 to 475 ft (137 to 145 m) below land surface. The well

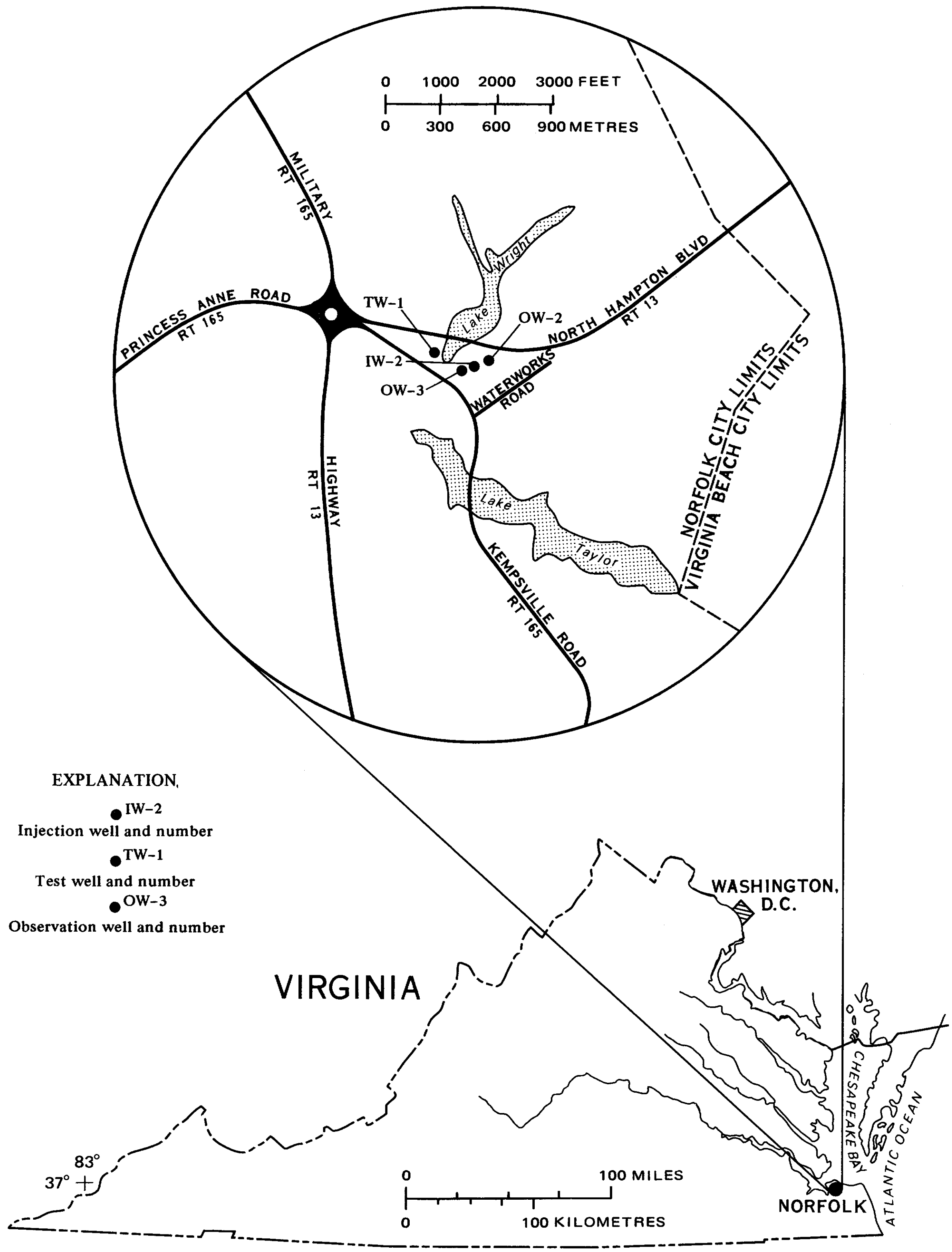


FIGURE 1.—Location of test site.

clogged during injection, but the withdrawal phase indicated the concept of recharge into brackish-water aquifers might be feasible.

ACKNOWLEDGMENTS

Charla Smith must be singled out for her competent assistance in the field work and data compilation. Her ability to keep the equipment functioning is directly responsible for much of the success of the project. The authors wish to acknowledge the assistance rendered by many Survey associates, but especially Robert L. Wait for his collaboration in the interpretation of current-meter data, Frank Koopman, Robert Wait, Jim Fickens, and Gordon Bennett for help in designing the injection system, Joe Pearson, Ivan Barnes, and Warren Wood for assistance in interpretation of geochemical data, and Francis Riley and John Roper for providing hydraulic conductivity tests on cores from the injection zone. Special thanks must also be given to former city councilman Paul Schweitzer and to James Kiracofe, chemist for the city of Norfolk, and to the personnel of the Norfolk Department of Utilities. Advice on the problems of clay dispersion was generously given by M. G. Reed, Chevron Oil Field Research; O. C. Baptist, U.S. Bureau of Mines; Wayne Hower, Halliburton; Bill Coulter, Dowell Division of Dow Chemical; and Charles Hewitt, Marathon Oil Company. Parts of the information used in this report has been previously published by the American Association of Petroleum Geologists as a paper by the authors entitled "Underground Storage and Retrieval of Fresh Water from a Brackish-Water Aquifer" (Brown and Silvey, 1973). Thanks are given to AAPG for use of these data in this report.

WELL FIELD

The well field (fig. 2) consists of the injection well (IW–2) and four observation wells. The observation wells are designated as follows: Annular-space well (ASW); observation well 2 (OW-2); observation well 3 (OW-3); and test well 1 (TW-1). All wells, with the exception of TW-1, were constructed of fiberglass casing with fiberglass or stainless-steel screens so that the materials used in the well construction would contribute no chemical influences in the experiment.

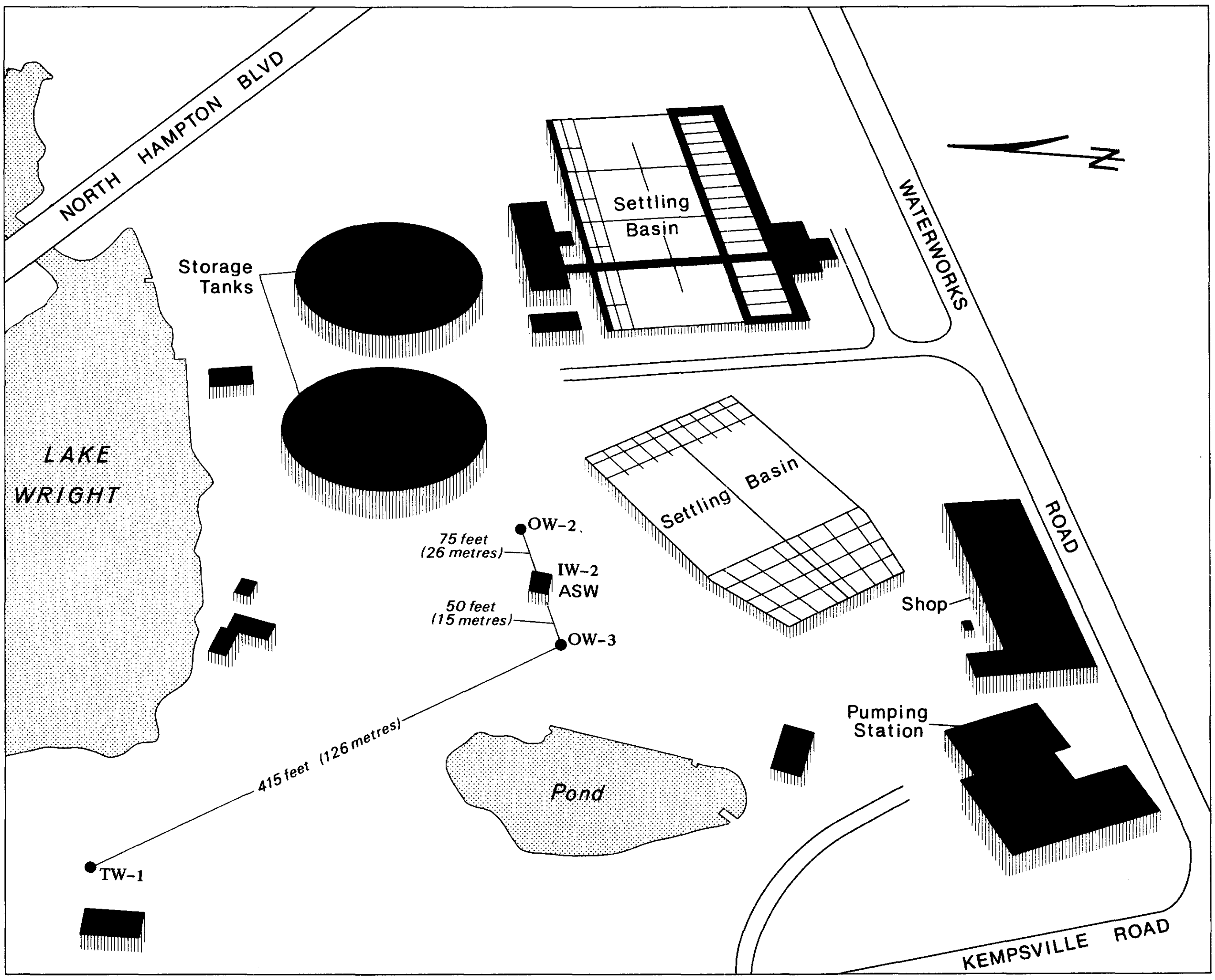


FIGURE 2.—Norfolk injection project well field, Moore's Bridges Filter Plant.

INJECTION WELL 1 (IW-1)

IW-1 was the initial attempt at constructing an injection well. The 18-in (460-mm) fiberglass casing collapsed at a depth of about 51 ft (16 m) below land surface, prior to cementing the casing in place. Salvage attempts failed, and the well was abandoned and filled with cement. The well is 25 ft (8 m) northeast of IW-2 and is in the same plane as IW-2, OW-3, and OW-2.

INJECTION WELL 2 (IW-2)

The design and construction of the injection well is shown in figure 3. The wall thickness of the 18-in (460-mm) casing is 0.5 in (13 mm) and has a theoretical ultimate collapse strength of 70 lb/in^2 (483 kPa). The wall thickness of the 8-in (200-mm) diameter casing is 0.4 in (10 mm) and has an ultimate collapse strength of 300 lb/in^2 (2068 kPa). The lowermost sections of both the 8-in (200-mm) and the 1.5-in (38-mm) pipe have stainless-steel nipples wound into the fiberglass. The stainless-steel screens are welded to the nipples using stainless-steel welding rods. Eighty feet (24 m) of wire-wrapped, 40-slot, stainless-steel screen is attached to both the 8-in (200-mm) casing and the 1.5-in (38-mm) pressure-monitoring pipe. (The 1.5-in (38-mm) well is described in the section "Annular-Space Well".) Both screens have 10 ft (3 m) of blank stainless-steel pipe at the bottom for sand traps. The slot size of the screens was determined from mechanical analysis of the sand recovered from cores taken in the injection zone. The entire injection zone from 896 to 976 ft (273 to 297 m) below land surface was screened.

A 4-in (100-mm) fiberglass instrument access pipe (fig. 3) extends below the pump bowls and is used for insertion and withdrawal of the current meter and other monitoring equipment as needed. Water is injected into the aquifer through a 4-in (100-mm) fiberglass line that enters the 18-in (460-mm) casing at a depth of 125 ft (38 m) below land surface.

OBSERVATION WELLS

ANNULAR-SPACE WELL (ASW)

The purpose of the 1.5-in (38-mm) annular-space well (ASW) is to monitor pressure-head changes in the gravel pack of the injection well during injection and withdrawal tests. To accomplish this, the screen was attached parallel to, but separated from, the screen of the injection well (IW-2) by 1-in (25-mm) wooden blocks. The screen is 1.25 in (32 mm) in diameter, heavy-duty, wire-wrapped, 40-slot, stainless steel. The entire injection zone is screened from 896 to 976 ft (273 to 297 m) below land surface, with a 10-ft (3-m) fill-up pipe from 976 to 986 ft (297 to 300 m) that is a sand trap.

OBSERVATION WELL 2 (OW-2)

OW-2 is 75 ft (23 m) northeast of the injection well and lies in a plane through IW-2 and OW-3. The casing and screen are 4.37-in (111-mm) inner diameter, epoxy-resin fiberglass having a wall thickness of 0.25 in (6.3 mm). The screen was made by sawing horizontal slots 0.05 in (1.3 mm) wide in a regular section of casing. The entire thickness of sand is screened from 900 to 990 ft (274 to 302 m) below land surface, and there is a 10-ft (3-mm) section of fill-up pipe from 990 to 1,000 ft (302 to 305 m) below land surface. The well is gravel packed to a height of 60 ft (18 m) above the screen and is cemented from that point upward to land surface.

OBSERVATION WELL 3 (OW-3)

OW-3 is 50 ft (15 m) southwest of the injection well. The construction of OW-3 is identical to that of OW-2, with the exception that 81 ft (25 m) of saw-slotted screen was installed. The entire thickness of sand is screened from 900 to 981 ft (274 to 299 m) below land surface, and there is a 10-ft (3-m) fill-up pipe from 981 to 991 ft (299 to 302 m) below land surface.

TEST WELL 1 (TW-1)

TW-1 is 415 ft (126 m) northwest of the injection well. TW-1 was a test well originally drilled to a depth of 2,587 ft (788 m) to determine the local geology, to define an injection zone, and to determine whether fresh ground water was present at depth (fig. 4). The water became increasingly saline with depth and was brine below 2,000 ft (610 m). TW-1 was backfilled with cement to 1,000 ft (305 m) below land surface and was completed as an observation well, partially penetrating the injection zone. The hole was under-reamed to a diameter of 24 in (610 mm) from 890 to 970 ft (271 to 296 m) below land surface. Sixty feet (18 m) of 6-in (150-mm) stainless-steel shutter screen (0.055-in or 1.4 mm openings) was set from 900 to 960 ft (274 to 293 m) below land surface with a 10-ft (3-m) fill-up pipe from 960 to 970 ft (293 to 296). Six-inch (150-mm) mild steel casing extends from the screen to land surface. The casing is cemented from the top of the gravel pack to the surface.

GEOLOGY AND HYDROLOGY OF THE INJECTION SAND

The aquifer chosen for the injection zone is a moderately sorted, angular to sub-angular, fine- to medium-grained, poorly cemented quartz sand of Cenomanian-Albian age (Brown, 1971). Wood fragments, ostracodes, and foraminifers recovered in cores, as well as textural features of the sand, suggest it is marine and was deposited in a littoral environment, possibly a tidal flat. The size and angularity of the quartz grains indicate a lower energy level than would be expected in an open beach or bar environment and probably indicate a semi-protected shoreline.

During coring attempts in TW-1, the sand in the injection zone was so unconsolidated that standard wire-line coring techniques did not obtain satisfactory core recovery. For this reason, a special "rubber sleeve" core

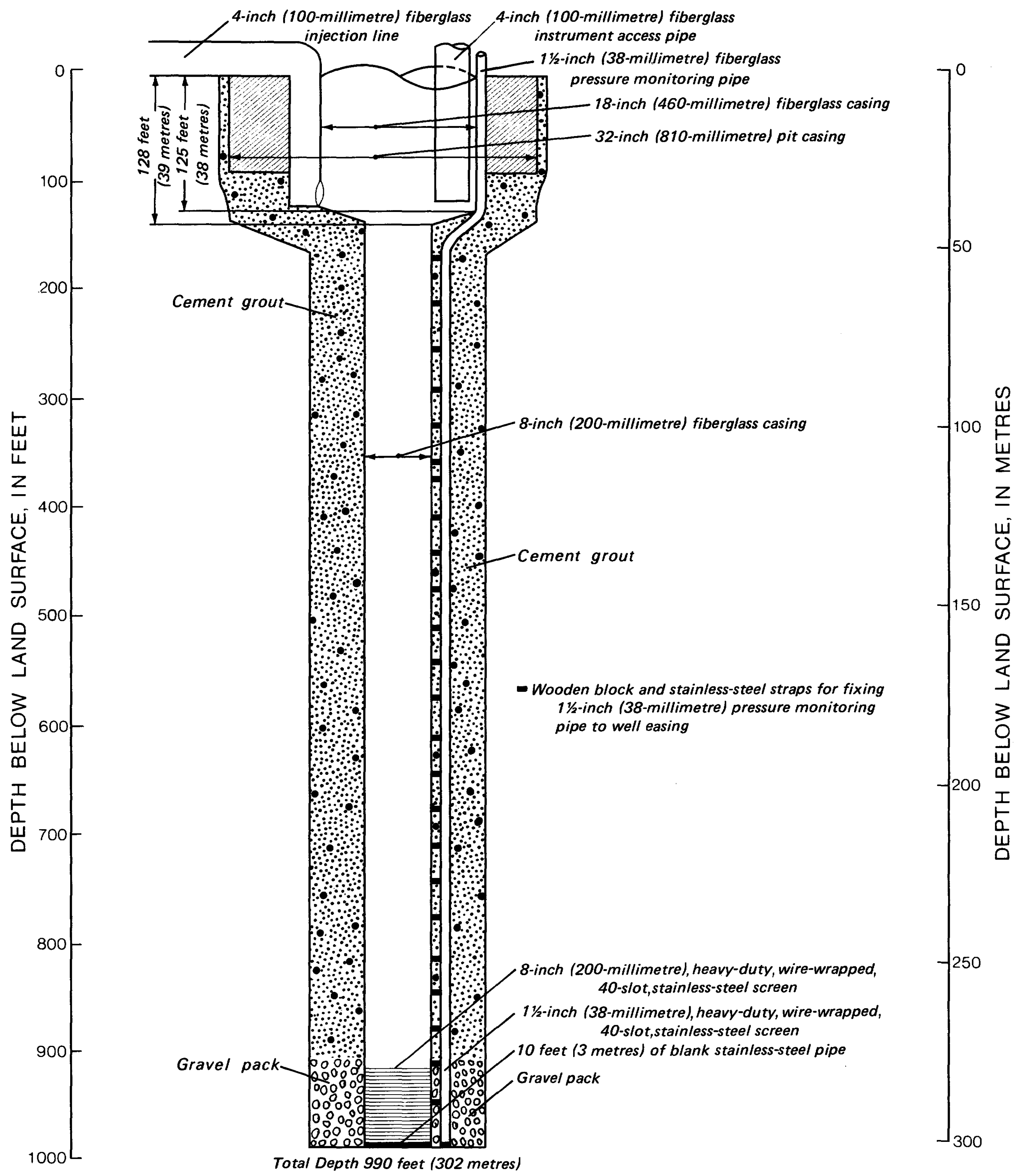


FIGURE 3.—Diagrammatic sketch of injection well IW-2.

barrel was employed to core the injection zone in OW–3. The tool is designed to take core in unconsolidated material by encasing the core in a rubber sleeve as the core is cut. Selected intervals of the core were submitted to the Geological Survey laboratory in Denver, Colo., for determination of clay type, grain size, porosity, hydraulic conductivity, and identification of mineral content of the sand.

Table 1 lists the accessory minerals identified by William Lockwood of the laboratory. Figure 5 is a

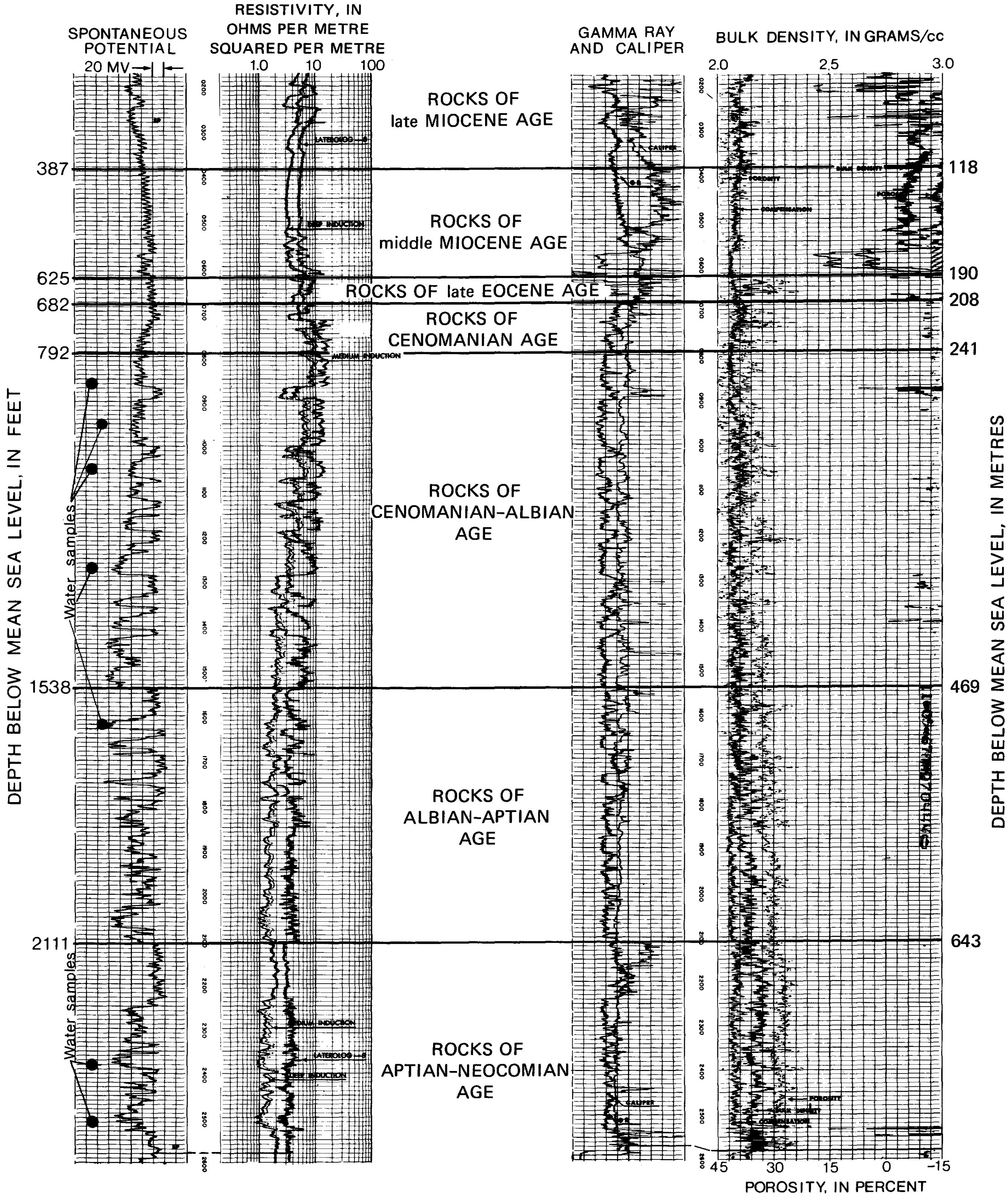
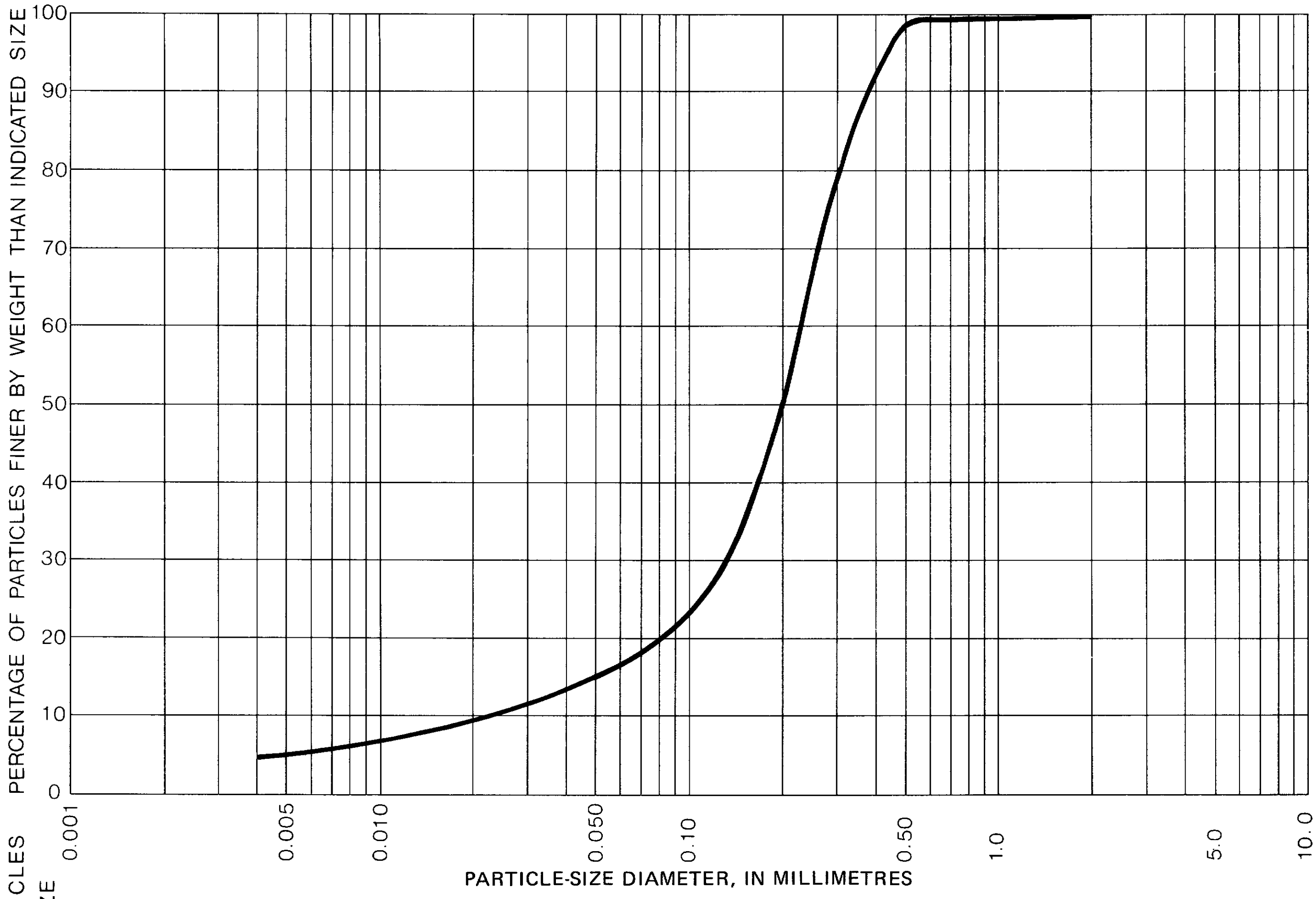


FIGURE 4.—Geophysical logs and stratigraphy of test well TW-1.



PERCENTAGE OF PARTICLES OF INDICATED SIZE

CLAY >0.004	SILT 0.004–0.0625	SAND					GRAVEL
		Very fine 0.0625–0.125	Fine 0.125–0.25	Medium 0.25–0.50	Coarse 0.5–1.0	Very Coarse 1.0–2.0	
5.0	12.2	9.8	39.4	33.0	0.6	0.2	0

FIGURE 5.—Composite cumulative curve of particle-size distribution of the injection sand.

cumulative curve showing the distribution of grain sizes by percent of the total weight. The curve is a composite of particle-size analyses of four cores taken at selected depth intervals in the injection zone. Using figure 5 and the statistical parameters shown in table 2, a description of the injection sand can be obtained.

The injection zone is bounded above and below by laterally persistent silty-clay to clayey-silt confining beds (fig. 6). The clay in the confining beds was identified by X-ray analysis as a multi-layered mixture of illite and montmorillonite, plus montmorillonite and minor amounts of kaolinite (table 3).

Because the montmorillonite and mixed-layer clays are swelling clays, the amount of these clays present in the injection sand was of concern. If the clay percentage was significant and swelling occurred when the clay was subjected to freshwater, the hydraulic conductivity of the injection zone would be decreased. To determine the spacial relationship of the clay and sand, several thin sections were prepared by the laboratory from the OW-3 core. A red thermosetting plastic was injected into the core under a vacuum while the core was still in the rubber sleeve. The "original" fabric, pore pattern, effective porosity, and interstitial relationship of the clay was thus preserved (fig. 7).

Figure 7 shows slight cross-bedding and a minor amount of interstitial clay. Even though table 3 shows that the clay content in the injection sand is as high as 25 percent, the interstitial clay content (fig. 7), which caused the clogging problems, is as low as 5 percent of the total

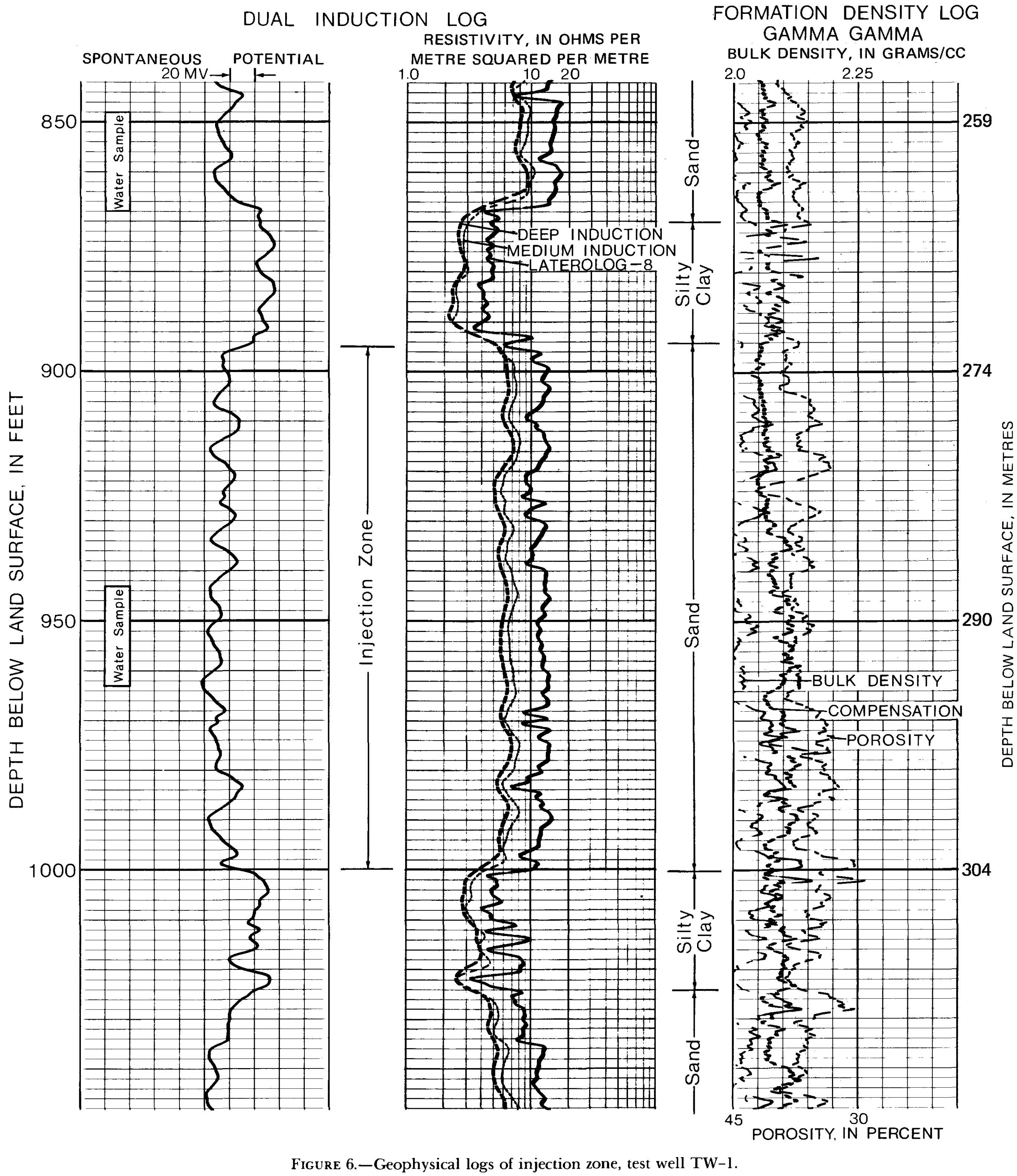


FIGURE 6.—Geophysical logs of injection zone, test well TW-1.

TABLE 1.—*Heavy minerals identified from cores of injection zone of observation well OW-3*

	Sample No.							
	69Va-1	69Va-2	69Va-3	69Va-4	69Va-5	69Va-6	69Va-7	69Va-8
Interval (ft)	892–912	912–932	975–995	892–912	912–932	935–955	955–975	955–975
Lithology	clay	clay	clay	sand	sand	sand	sand	sand
Percent of sample								
Total heavy minerals	0.8	0.5	0.3	1.3	4.0	0.6	0.9	1.3
Percent of total heavy minerals								
Apatite	.....	.....	<1	.....	.....	.....	.....	.....
Amphibole	.....	.....	1	.....	.....	.....	.....	.....
Actinolite	.....	.....	<1	2	2	2	1	.....
Tremolite	.....	.....	<1	.....	.....	.....	1	.....
Biotite	<1	13	.....	.....	.....	2	1	1
Chlorite	4	12	1	.....	.....	.....	1	.....
Diopside	.....	<1	<1	1	.....	1	2	.....
Epidote	<1	<1	<1	5	4	19	9	5
Garnet	.....	5	<1	10	10	15	5	15
Hornblende	.....	<1	1	.....	.....	.....	.....	4
Hypersthene	.....	.....	<1	.....	.....	.....	.....	.....
Kyanite	.....	.....	<1	1	<1	1	1	1
Magnetite	.....	11	24	23	20	24	27	29
Muscovite	1	4	8	2	9	1	1	2
Pyrite	85	4	9	7	.....	3	10	.....
Rutile	.....	<1	<1	.....	.....	.....	1	.....
Staurolite	.....	14	5	14	22	12	25	19
Titanite	.....	.....	3	5	2	.....	1	.....
Tourmaline	.....	<1	<1	2	<1	1	1	.....
Zircon	.....	<1	1	.....	.....	1	2	.....
Unidentifiable	9	35	45	28	30	18	21	14

TABLE 2.—*Statistical parameters of the injection sand*

Phi parameter	Value (phi units)	Remarks
Mean	2.3	Fine sand
Standard deviation	1.3	moderately sorted
Skewness coefficient	0.46	Slightly skewed (slightly poorer sorting in fine sizes)
Kurtosis coefficient	2.6	Moderately peaked (better sorted in the center than on the two ends)

clay content. The relatively small amounts of interstitial clay present in the thin sections appeared to negate a clogging problem. However, it is now apparent that a very small percent of clay can significantly reduce hydraulic conductivity. Moreover, the injection well (IW-2) is in an area of facies change that has an increase in the percentage of silt and clay in the injection zone (table 4). The effect of the clay on the hydraulic conductivity will be discussed in detail later in the paper.

The formation water in the injection zone is brackish having a dissolved-solids concentration of 3,010 mg/l (milligrams per litre). It is a sodium chloride bicarbonate type water having a chloride concentration of 1,360 mg/l. A detailed description of the chemical quality of the native ground water is presented later in the paper.

TABLE 4.—*Thickness and sand-shale ratios for the injection zone within the well field*

Well	Depth to top of injection sand (ft below sea level)	Thickness (ft)	Total sand (percent)	Sand-shale ratio upper half	Sand-shale ratio lower half
TW-1	885	104	83.0	81.0	85.0
OW-2	889	86	84.0	84.0	84.0
OW-3	891	82	83.0	76.0	90.0
IW-1	891	88	63.0	77.0	48.0
IW-2	888	84	59.5	79.0	40.5

AQUIFER TESTS

Constant-rate and step-drawdown aquifer tests were made on IW-2 and TW-1. Consistent transmissivity values were not obtained from interpretations by the Theis method of analysis or by the "leaky aquifer" analysis. Slope changes indicating recharge boundary conditions

TABLE 3.—*X-ray diffraction analysis of core samples from injection zone, observation well OW-3*
[Results in percent]

Depth[1] of sample (ft)	Lithology	Quartz	Feldspar	Kaolinite	Illitic-mica	Mixed-layer clays	Montmorillonite	Chlorite	Total
892–912[2]	Clay	32	16	5	17	30	.....	.....	100
975–995[2]	Sand	71	6	4	6	13	.....	.....	100
975–995[2]	Sand	78	5	3	4	10	.....	.....	100
892–912[3]	Clay	20	12	13	27	.....	18	.....	90
892–912[3]	Sand	52	24	3	3	1	18	.....	101
935–955[3]	Sand	67	23	1	1	.....	2	1	95
955–975[3]	Sand	52	19	7	7	.....	2	2	89

[1]Core was recovered in 20-foot lengths and the lithology varies considerably within a cored interval.

[2]Core analysis by Wayne Hower of Halliburton Company who reported that dye staining of consolidated fragments of the core showed the kaolinite was limited to isolated "clumps" whereas the mixed-layer clays were present in the waterways. In his opinion, the core would be "quite sensitive to freshwater" (Hower, oral commun., 1972).

[3]Core analysis by Barbara Anderson, U.S. Geological Survey, Denver, Colo.

FIGURE 7.—Thin section of part of the injection sand (955 to 975 ft or 291 to 297 m).

begin affecting the aquifer-test data after 10 minutes of pumping and continue to affect the logarithmic plots up to about 60 minutes. Apparent recharge occurs in the plot of both drawdown and recovery data and has been interpreted as indicating thickening of the producing aquifer or increased permeability in the aquifer away from the well field.

On the basis of the aquifer-test data and an interpretation of the geology, a geologic model was made of the aquifer. This interpretation theorized a gently arcuate, concave westward, sand buildup striking north-northeast lying to the west of the well field. The eastern limit of the buildup passes close to the western edge of the well field.

Using the geologic framework and the aquifer-test data, O. J. Cosner of the Geological Survey constructed a mathematical model of the hydrology of the well field. Values of transmissivity ranged from as low as 5,360 $ft^3d^{-1}ft^{-1}$ or 498 $m^3d^{-1}m^{-1}$ in the injection well to 16,600 $ft^3d^{-1}ft^{-1}$ or 1,540 $m^3d^{-1}m^{-1}$ in the area of maximum sand buildup. In areas other than the sand buildup or the actual well field, a regional transmissivity value of 8,300 $ft^3d^{-1}ft^{-1}$ or 770 $m^3d^{-1}m^{-1}$ was used. The digital model included a 20-ft (6-m) layer of clay above the injection sand that had a vertical hydraulic conductivity of 1.41×10^{-5} ft/d (4.3×10^{-6} m/d). The specific storage of the confining clay was assumed to be 4×10^{-5}. The storage coefficient of the aquifer, determined from tests, was 1.5×10^{-4}.

The model was verified by simulating drawdown and recovery curves obtained from a 48-hour aquifer test in which IW–2 was pumped at 800 gal/min (50 l/s) and TW–1 was observed. The model shows that after pumping or injecting on a long-term basis (4 days or more), water levels would tend to stabilize because of leakage through the confining layers (Cosner, oral commun., 1970). No long-term aquifer tests were made to establish the validity of the model-derived hydraulic conductivity of the confining bed.

Several constant-rate pumping tests and a 3-hour step-drawdown test were made of IW–2 to determine specific capacities prior to any injection (table 5). Step-drawdown tests were made to determine the well loss to be expected when withdrawing water at a rate double that of injection. Figure 8 is a hydrograph of the step-drawdown test made of IW–2 showing how the specific capacity values were derived. The well was pumped with a 10-in (250-mm) turbine pump, and the discharge measured by 10- by 6-in and 10- by 5-in (250- by 150-mm and 250- by 130-mm) orifice plates. Water-level measurements were made during pumping and recovery in the pumped well IW–2 and in observation wells OW–2, OW–3, and TW–1. Comparison of the specific capacities obtained during withdrawal and injection tests will be presented later in the paper.

TABLE 5.—*Specific capacities at various pumping rates after 1 hour for the injection sand on test well TW–1 and injection well IW–2*

Well	Date	Screened interval (depth in ft)	Type of test	Pumping rate (gal/min)	Specific capacity (gal $min^{-1}ft^{-1}$)
TW–1	3- 7-69	900–960	step drawdown	100	17.7
TW–1	3- 7-69	900–960	step drawdown	150	13.7
TW–1	3- 7-69	900–960	step drawdown	250	12.1
TW–1	3-11-69	900–960	constant rate	200	13.0
IW–2	5-20-70	896–976	step drawdown	250	16.2
IW–2	5-20-70	896–976	step drawdown	500	15.8
IW–2	5-20-70	896–976	step drawdown	1000	13.4
IW–2	5-21-70	896–976	constant rate	800	14.5

INJECTION SYSTEM

All pipes and valves are constructed of schedule 80-polyvinyl chloride. All waterways in the pumps are either rubber lined or epoxy coated so at no place in the system is there iron in contact with the injection or withdrawal water, except as stainless steel. Chemically stable materials were used to prevent extraneous sources of iron masking chemical reactions occurring within the aquifer.

The city water is injected by a 10-horsepower (7.46 kW) centrifugal pump rated at 500 gal/min (31.5 l/s) against a total dynamic head of 30 ft (9 m). It operates at 800 revolutions per minute. The pump will deliver 800 gal/min (50.5 l/s) to free discharge at the well house which is located 230 ft (70 m) from the centrifugal-pump vault. The pump vault is situated adjacent to a 60-in (1,520-mm) concrete line from which the injection water is supplied. The centrifugal pump has a rubber liner so that the city water is not in contact with any ferrous-metal surfaces prior to injection.

The injected water is withdrawn by a 30-horsepower (22 kW), 10-in (250-mm), vertical hollow-shaft turbine pump rated at 800 gal/min (50.5 l/s) against a total dynamic head of 105 ft (32 m). It has 120 ft (37 m) of 8-in (200-mm) epoxy-coated pump column and a four-stage stainless-steel pump-bowl assembly. All waterways are epoxy coated.

The injection flow system is so arranged that water flows in the same direction through the metering system during either injection or withdrawal. The metering system consists of a 4.8-in (122-mm) stainless-steel orifice plate and a McCrometer[1] Model MC 01400 saddle meter. One-inch (25-mm) diameter, thin wall, polyvinyl chloride pipes in 10-in (250-mm) lengths are cemented in the 6-in (150-mm) flow line both upstream and downstream from the orifice to act as straightening vanes and eliminate turbulent flow through the orifice. Pressure changes between the upstream and downstream sides of the orifice are recorded by a differential pressure transducer. The orifice was calibrated in the laboratory prior to installation.

[1]The use of trade names does not imply endorsement by the U.S. Geological Survey but is provided for complete description of the system.

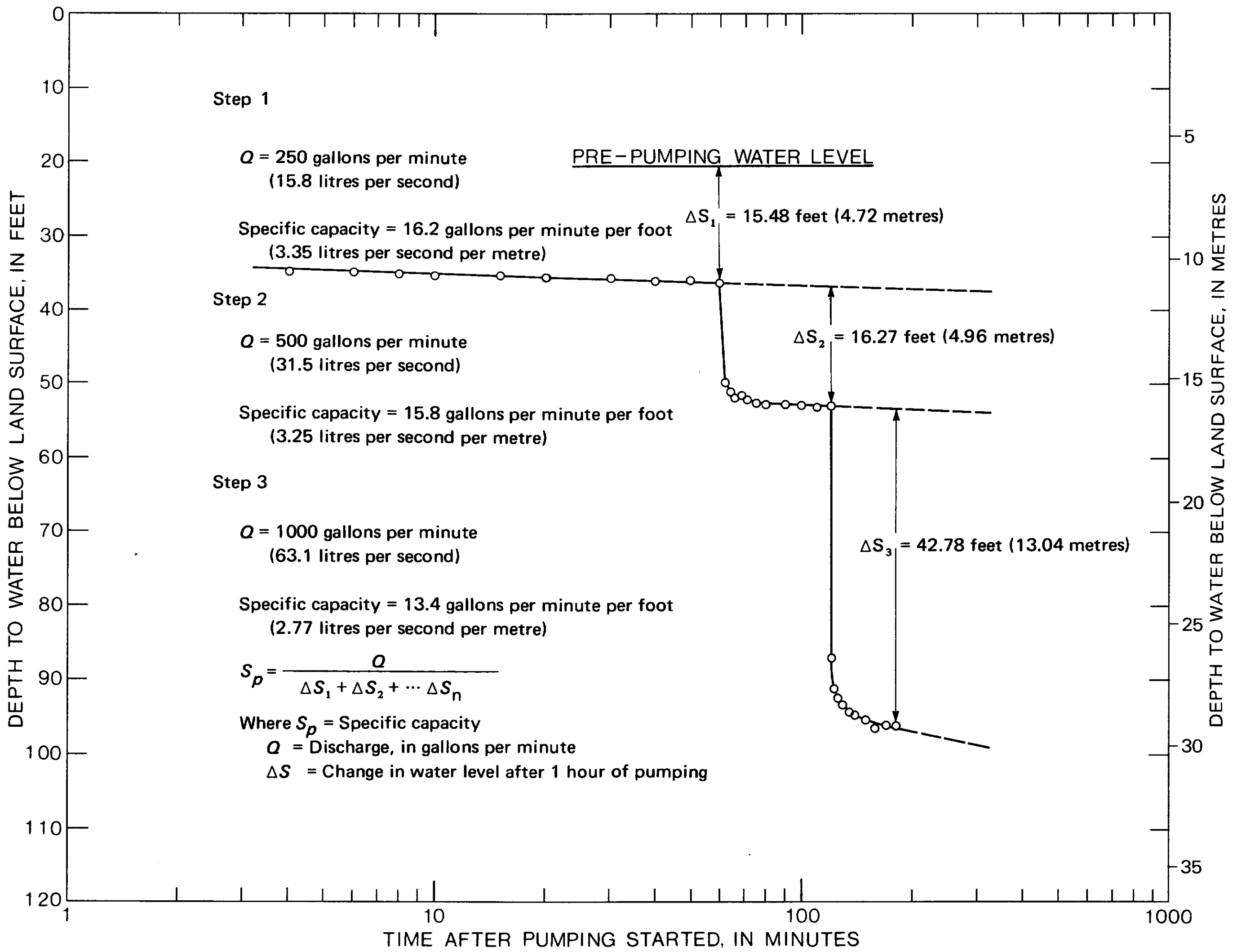


FIGURE 8.—Hydrograph of injection well IW-2 showing specific capacities derived from May 1970 step-drawdown test.

The saddle meter registers both the rate in gallons per minute and the total flow. It was calibrated against the orifice in the laboratory prior to installation. The reproducibility of the saddle meter versus orifice data is accurate to a maximum positive deviation of 0.59 percent and a maximum negative deviation of 0.97 percent.

PRE-INJECTION CALIBRATIONS

CURRENT METER

To determine if clogging was occurring during injection, it was necessary to determine which parts of the aquifer in IW-2 were contributing water during pumping of the well. Current-meter traverses were made of the screened interval in IW-2 before, during, and after injection tests to evaluate the clogging data.

An Au deep-well impeller-type current meter was used for these tests. The current meter is in the top of a 3-ft (0.9-m) tube. Water enters the bottom of the tube and flows vertically through it, causing the impellers to spin about the vertical shaft of the current meter. A magnetic switch is activated once each revolution and sends a signal through a single conductor cable to a counter at the surface.

With the current meter hanging freely in the upper part of the screen that contribures no flow from the aquifer, the discharge was varied to calibrate the meter by establishing a revolutions-per-minute to gallons-per-minute relation. IW-2 was then pumped at a constant rate of 770 gal/min (49 l/s), and a current-meter traverse was made of the screened part of the aquifer at 1-ft (0.3-m) increments. The traverse was repeated using a constant discharge rate of 400 gal/min (25 l/s). These two traverses (fig. 9) show the pre-injection flow patterns in the aquifer at the proposed injection rate (400 gal/min or 25 l/s) and withdrawal rate (770 gal/min or 49 l/s). The traverses indicated that 45 percent of the water came from the zone 908 to 923 ft (277 to 281 m) and 39 percent from 950 to 972 ft (290 to 296 m) below sea level. Other minor zones of contribution were present.

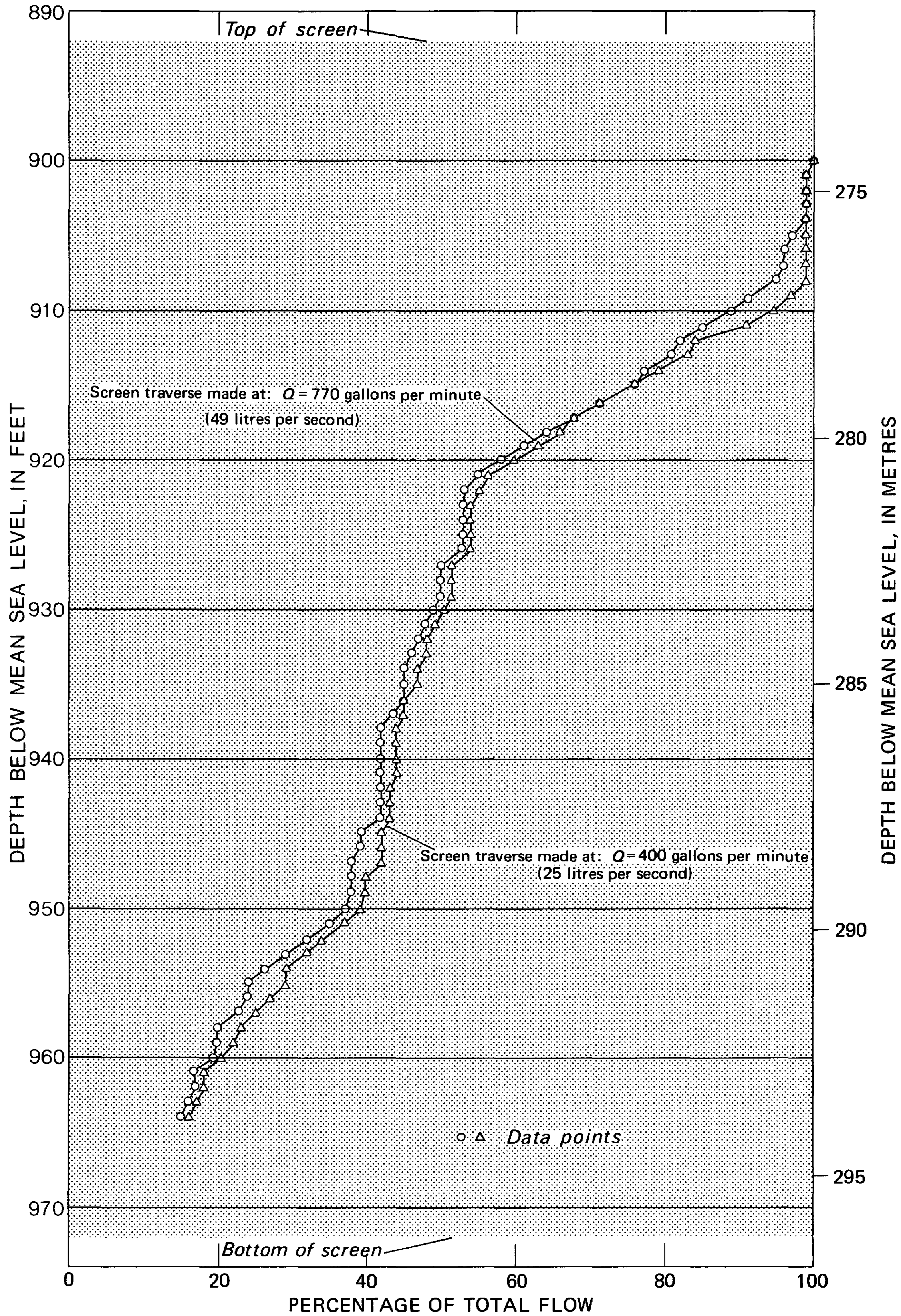


FIGURE 9.—Current-meter traverses in injection well IW-2 prior to injection of freshwater.

TRANSDUCERS

Transducers were used to measure water-level changes during injection and withdrawal. Solid state, semiconductor pressure transducers with ranges of ±40 lb/in^2 (±276 kPa) were used in wells IW–2 and ASW. The transducers will measure a total change in water level of about 100 ft (30 m). The water level changes in OW–3 were not as great as in the pumped well; therefore, a ±15-lb/in^2 (±103-kPa.) transducer was used. It will record a total head change of about 30 ft (9 m).

The transducer system of recording water levels or head changes did not prove reliable because they failed during long-term tests. The transducers were submerged during the tests, and it was especially difficult to keep the electrical connections waterproofed under high heads in fresh water and also under static conditions in saline water. Their accuracy, when functioning properly, was reproducible within 0.1 percent of the total range.

A 0 to 5 lb/in^2 (0 to 34 kPa) variable reluctance differential transducer was located in the flow system to measure the change in head as the water passed through the orifice. The transducer box was connected to the upstream and downstream sides of the orifice by means of plastic tubes leading to taps installed in the 6-in (150-mm) pipe. The orifice was calibrated in the laboratory by a transducer system so that pressure changes may be directly converted to gallons per minute.

TURBIDITY

It was necessary to establish a relationship between turbidity recorded in Jtu's (Jackson turbidity units) and suspended solids to determine the volume of sediment being injected into or withdrawn from the aquifer. A Hach Model 1889 Surface Scatter Turbidometer was used to measure turbidity. Samples were collected at various Jtu values, then filtered, and the filtrate weighed to establish the relation.

Turbidity was measured to determine if the particulate matter injected into the aquifer was recovered. It it could be shown that the volume of sediment recovered during withdrawal was less than was injected, it could be assumed that the aquifer was being clogged by particulate matter in the injection water. The amount of suspended sediment in the injection water is small (a maximum of 1 to 2 mg/l).

WATER-QUALITY MONITOR

The following parameters were measured by a water-quality monitor during both injection and withdrawal phases of any test: Conductivity, pH, Eh, temperature, dissolved oxygen (DO), turbidity, head changes in IW–2, ASW, OW–3, and orifice flow rate. Prior to each test, each sensor was calibrated to fit the expected range of values.

The data were recorded by two systems. A Fisher & Porter Model 1542 digital punch records the data from the monitor on digital tape at either 15-, 30-, or 60-min intervals, depending upon the choice of the operator. It takes 45 seconds to monitor a parameter, punch it, and move to the next parameter. A 16-channel strip-chart recorder served as a backup system. The strip chart records a parameter every 15 seconds and has a complete cycle time of 4 min. Parameters that show considerable variations with time or pumping rate, such as conductivity or depth to water, were recorded more than once in the 4-min cycle. The strip-chart record has the advantage that changes in data can be observed directly, whereas the digital tapes must be processed.

INJECTION TESTS

It was originally planned to conduct successive injection tests with the emphasis on injection of a large quantity of water and storing it for a long period of time prior to withdrawal. Modification of these plans became necessary because the injection specific capacity of the aquifer became so low during injection test 3 that it was impractical to continue the test beyond 1,100 min.

INJECTION TEST 1

The purpose of injection test 1 was to test the flow system and sensing apparatus; to determine the head buildup that would occur during long-term tests; to detect errors in calibration limits set for the monitoring equipment; to determine chemical reactions occurring during injection and withdrawal; and to establish the number of people required to conduct the tests. In accordance with these objectives, it was decided that the initial injection test would be of 8 hours duration.

Injection was begun at 0900 hours on Nov. 22, 1971, at a rate of 400 gal/min (25 l/s). This rate was held for 270 min, after which the injection pump was shut down to allow insertion of the current meter into the screen of IW–2. After a shut-down of 35 min, injection continued at 400 gal/min (25 l/s) for an additional 205 min until shut-down at 1730 hours on Nov. 22, 1971. No redevelopment pumping was attempted during injection of the water. A total of 198,320 gal (750 m^3) of city water was injected into the brackish-water aquifer. The water remained in place for 15.5 hours before withdrawal began.

Withdrawal of the injected water began at 0900 hours on Nov. 23, 1971, at a rate of 710 gal/min (45 l/s). The withdrawal rate gradually increased to 730 gal/min (46 l/s) by the end of the withdrawal phase (330 min of withdrawal) of test 1. A total of 250,210 gal (947 m^3) was withdrawn, or about 26 percent more water was removed than injected. During both injection and withdrawal, current-meter traverses were made of the screened section in IW–2 and conductivity profiles in OW–3 were made during the injection phase.

INJECTION TEST 2

The purpose of injection test 2 was to verify the chemical and physical data obtained in test 1. Although the results of test 1 were encouraging, the time span was so small that valid conclusions on long-term testing could not be made. Injection test 2 was designed to inject approximately 10 times the quantity of water of test 1 and to leave it in the aquifer for 48 hours. Conductivity surveys of the screened section of the nearest observation well (OW-3) were planned to determine the time of arrival of the injected water and to define the shape of the injection front at OW-3.

Injection test 2 began at 1400 hours on Feb. 14, 1972, and concluded after a total of 7,906 min (5.49 days). Injection was interrupted for 250 min after continuously injecting for 5,340 min (3.71 days) because of repairs to the city filter plant. The initial injection rate was 410 gal/min (26 l/s), but it gradually decreased to 215 gal/min (14 l/s) after 7,800 min (5.42 days) of injection. A total of 2,445,530 gal (9,260 m^3) of treated city water was injected into the brackish-water aquifer without any redevelopment pumping during the injection period. The water remained in the aquifer for 50 hours (2.08 days).

Withdrawal of the injection water began at 1100 hours on Feb. 22, 1972, and ended Feb. 26, 1972, at 1100 hours. A total of 3,504,100 gal (13,260 m^3) of water was withdrawn or about 43 percent more than was injected. Current-meter traverses of IW-2 and conductivity profiles of OW-3 were made during injection and withdrawal.

INJECTION TEST 3

The purpose of injection test 3 was to verify chemical and physical data obtained in tests 1 and 2 and to obtain additional data. The results of test 2, as in test 1, were encouraging regarding the practical use of the aquifer for storage of freshwater. However, the decrease in the injection rate and the excess head buildup near the end of test 2 were areas of concern. Injection test 3 was designed to inject about 10 times more water than in test 2 and to leave it in place a minimum of 2 weeks. Conductivity surveys of OW-3 were planned to compare the shape of the injection front and arrival time with the data of test 2.

Injection test 3 began at 1600 hours on Apr. 13, 1972. The injection rate dropped from an initial 400 gal/min (25 l/s) to 115 gal/min (7.3 l/s) within 80 min, and gradually decreased to a low of 70 gal/min (4.4 l/s). After injecting for 20 min, pressure on the discharge side of the injection pump rose from a normal value of 12 lb/in^2 (83 kPa) to the maximum value of 20 lb/in^2 (138 kPa). After 1,174 min (0.82 day) of constant injection, it was apparent that the aquifer would not take water in sufficient quantities to continue the test.

A total of 132,700 gal (502 m^3) of freshwater had been injected. In attempts to redevelop the well, water was alternately withdrawn and injected for a period of about 5 hours, resulting in a net additional 13,300 gal (50 m^3) of water being injected for a total of 146,000 gal (553 m^3). The water remained in place for 76.5 hours (3.2 days).

Withdrawal of the injected water began at 1000 hours on Apr. 17, 1972. A total of 318,000 gal (1,200 m^3) of water was withdrawn or 46 percent more than was injected. This total includes almost 95,000 gal (360 m^3) recovered during redevelopment attempts during injection. Current-meter traverses of IW-2 were made during injection and withdrawal.

At this point, a total evaluation of what was occurring within the aquifer had to be made before any additional injection tests could be attempted.

DETERIORATION OF AQUIFER HYDRAULIC PROPERTIES

It became increasingly apparent during the injection phase of test 3 that deterioration of the hydraulic properties was occurring because of injection of freshwater. Alteration of the aquifer and a resulting decrease in hydraulic conductivity was reflected by: (1) Excessive head buildup in the injection well and nearby observation wells; (2) alterations in flow gradients between wells; and (3) low injection rates into the aquifer.

It has been shown by many investigators (Baptist and Sweeny, 1955, 1957; White, Baptist, and Land, 1962, 1964; Hewitt, 1963; Meade, 1964; Gray and Rex, 1966; Reed, 1972) that a reduction in permeability of some aquifers occurs when the salinity of the pore water is altered. The reduction is greatest if the salinity is greatly reduced. A sand that exhibits this tendency is described as "water sensitive."

The greatest deterioration of the hydraulic properties of the water-sensitive aquifer is usually a result of physical movement of interstitial clay particles rather than clogging by chemical precipitation. Land and Baptist (1965, p. 1213–1218) have demonstrated that most of the reduction in hydraulic conductivity is due to dispersion of clay particles rather than in situ swelling of the clay.

Evidence of clay dispersion clogging versus in situ swelling is mostly indirect, but there are two criteria that may be used to determine which process is functioning: (1) Reduction in hydraulic conductivity due to swelling would be mostly reversible when original conditions were restored, whereas deterioration due to clay dispersion is largely irreversible. As the clay particles are dispersed, they move until they become lodged in pore constrictions, causing clogging. Returning the water chemistry to original conditions will not repack the clay in its original position. (2) If a section of core of the aquifer is saturated with formation water, then flushed with freshwater, a milky, turbid effluent accompanied by decreasing hydraulic conductivity usually results if clay dispersion is occurring.

The mechanism for clay dispersion has been reported in detail by Meade (1964), Jones (1964), Gray and Rex (1966), and Reed (1972) and will be discussed here only in general terms. Clay dispersion is predominately a result of electrokinetic properties. The electrostatic attraction between negatively charged clay particles and exchangeable cations is opposed by the tendency of the ions to diffuse and become uniformly distributed throughout an aqueous solution.

Meade, Gray and Rex, and Reed all state that one of the most significant factors causing dispersion is a change in the double-layer thickness surrounding a clay particle. The double layer exists because of a negative charge on the surface which attracts cations close to this surface. Because the fluid must retain its electrical neutrality, a more diffuse second zone of anions are attached to the attached cations. This forms a double layer of ions surrounding each particle.

When the concentration of ions is large, as in the case of brackish water, the double layer on the particle is compressed to a small thickness. Compression of the double layer permits clay particles to coalesce, due to interparticle attraction of van der Waals forces, and form larger aggregates that can overcome the disrupting Brownian movement and therefore promote gravitational settling. This is commonly called clay flocculation. When the concentration of ions in a fluid is low, as in the case when dilute freshwater enters the aquifer, the diffuse double layer expands, forcing the clay particles apart. This expansion prevents the clay particles from coming close together to aggregate, therefore keeping them dispersed and in suspension. This is commonly referred to as clay dispersion.

The tendency to disperse is measured by the zeta potential

$$Z=\frac{4\pi\delta q}{D}, \tag{1}$$

where δ=thickness of the zone of influence of the charge particle;
q=charge on the particle before any cations are attached;
D=dielectric constant of the liquid.

For any given solution and colloid, reduction of the zeta potential is accomplished by reducing the thickness of the zone of influence. This is accomplished by increasing the charge density as close to the surface of the particle as possible by substituting small doubly or triply charged ions such as Al^{+3} or Ca^{+2} in place of large singly charged hydrated ions such as Na^{+1}. This ionic substitution gives a smaller zeta potential and permits clay particles to coalesce. Highly hydrated ions, such as sodium, result in a clay-cation system with high zeta potential. The water of hydration prevents the cation from being closely adsorbed. These facts may account for the tendency of sodium to cause dispersion of clay colloids and for calcium to cause flocculation.

Sands containing montmorillonite and mixed-layer clays that are small in size and have large surface charges are usually the most water sensitive. As little as 0.4 percent montmorillonite has caused a 55-percent reduction in hydraulic conductivity (Hewitt, 1963, p. 817). The clay present in the injection zone, as shown by X-ray studies (table 3), has sufficient quantities of montmorillonite, illite, and mixed-layer clays to account for the reduction in hydraulic conductivity that occurred during injection tests 1, 2, and 3.

HEAD BUILDUP

The first evidence of formation alteration due to injection of the freshwater was the excess head buildup that occurred in the injection well during injection test 1. The expected head buildup in each well was determined by a pre-injection pumping test in which IW–2 was pumped at 400 gal/min (25 l/s) for 8 hours. The inverse of the drawdown measured in each well was used to predict head buildup when the injection rate was 400 gal/min (25 l/s).

EXCESS HEAD BUILDUP DUE TO TEMPERATURE AND VISCOSITY

In the pumping well (IW–2) and annular space well (ASW), the effects of density and temperature were taken into consideration in calculating the expected head buildup using a method described by G. D. Bennett (written commun., 1969). The formulas for the radius of intrusion of the injection water and for the excess head buildup are as follows:

The radius of intrusion can be derived from the formula for the radius of a cylinder:

$$r=\sqrt{\frac{V}{\pi h}}, \tag{2}$$

where V=volume of the cylinder;
h=height of the cylinder.

If a porosity factor (θ) is used to compensate for the void spaces, the volume (V) is represented by the injection rate (Q) and length of injection ($t-t_c$), the length of the screened area (D) represents the height (h) of the cylinder, and the effect of the radius of the well (r_w) is considered, then equation 2 can be rewritten as follows:

$$r_i(t)=\sqrt{\frac{Q(t-t_c)}{\pi D\theta}+(r_w)^2}, \tag{3}$$

where $r_i(t)$=the radius, in feet, of the injection water (colder water) at time (t);
r_w=the radius of the well, in feet;
Q=the flow rate, in cubic feet per minute;
$t-t_c$=the time that the colder water has been in the aquifer, in minutes;
D=the length of screen, in feet;
θ=porosity, expressed as a decimal.

The excess head buildup can be calculated using a modification of the standard distance-drawdown formula;

$$T=\frac{2.3Q\log_{10}r_2/r_1}{2\pi(s_1-s_2)}, \tag{4}$$

where T=transmissivity, in cubic feet per day per foot;
Q=rate of discharge of the pumped well, in gal/min;
r_2=distance from the pumped well at which drawdown is desired, in feet;
r_1=radius of the well, in feet;
s_1-s_2=drawdown, in feet.

If transmissivity is represented by the hydraulic conductivity (K) times the thickness of the aquifer screened (D), excess head buildup ($S_{wTt}-S_{wt}$) is substituted for drawdown (s_1-s_2), and the radius of the injection front ($r_i(t)$) is substituted for r_2, then equation 4 can be rewritten as follows:

$$S_{wTt}-S_{wt}=\left(\frac{1}{K_{1c}}-\frac{1}{K_1}\right)\left(\frac{2.3Q}{2\pi D}\right)\left(\log\frac{r_i(t)}{r_w}\right), \qquad (5)$$

where $S_{wTt}-S_{wt}$=excess head buildup, in feet, due to colder water (head buildup in IW-2 for injection water of temperature T, at time t, minus head buildup in the well for the formation water at time t);
K_1=horizontal hydraulic conductivity of the formation to formation water, in cubic feet per minute per square foot;
K_{1c}=horizontal hydraulic conductivity of the formation to freshwater at the injection temperature, in cubic feet per minute per square foot. $K_{1c}$is defined as $K_1(u/u_c)$, where u_c is the viscosity of cold freshwater at injection temperature and u is the viscosity

The following assumptions are used in making the calculations: The water moves into the formation in a horizontal, radial pattern; it remains confined in the 80-ft (24-m) zone in which the well screen is placed; accumulation of water in storage within the radius $r_i(t)$ is negligible for any time t during the test; and a definite interface exists between the colder denser injection water and the formation water. If the average transmissivity based on pumping-test data between well OW-3 and IW-2 is taken as 7,075 $ft^3d^{-1}ft^{-1}$ ($657m^3d^{-1}m^{-1}$), the following substitutions can be made in equations 3 and 5:

K_1=0.061 $ft^3min^{-1}ft^{-2}$;

K_{1c}=0.041 $ft^3min^{-1}ft^{-2}$, taking the water temperature of the injection water as 10°C, its viscosity as 1.3 cP (centipoises) and the viscosity of the formation water as 0.87 cP;

Q=400 gal/min or 53.5 ft^3/min;

D=80 ft;

r_w=0.33 ft;

θ=0.30 (the porosity of the injection sand was obtained from core analysis and interpretation of compensated gamma-gamma density logs. Both sources indicated an effective porosity of 35 to 40 percent. A value of 30 percent is used here, as a part of the effective porosity is always occupied by essentially static water along the pore walls).

After 1 minute of injecting 10°C water, the radius of the injection water from the well would be:

$$r_i(t)=\sqrt{\frac{(53.5)(1)}{(3.14)(80)(0.3)}+(0.33)^2},$$

$r_i(t)$=0.905 ft (0.28 m).

Solving equation 5 gives:

$$S_{wTt}-S_{wt}=\left(\frac{1}{0.041}-\frac{1}{0.061}\right)\cdot\frac{(2.3)(53.5)}{(2)(3.14)(80)}\cdot\log\frac{0.905}{0.33}$$

$S_{wTt}-S_{wt}$-0.87 ft (0.26m) of excess head buildup after 1 minute due to colder water.

The negative of the drawdown curve from a pre-injection aquifer test was used as the head buildup to be expected in the wells. The calculations for excess head were added to the inverse drawdown plot in order to approximate head buildup changes with time and temperature. The equations were solved for excess head buildup changes with time and temperature. The equations were solved for excess head buildup at various temperatures and times so that predicted head buildup could be approximated prior to any injection test. The difference in temperature between the city water and formation water may vary as much as 20°C depending upon the season.

Figure 10 shows plots for IW-2 and OW-3 of the theoretical head buildup divided by discharge and actual head buildup divided by discharge recorded during the first 270 minutes of injection test 1.

The figure shows that the theoretical data approach the empirical data in the observation well, but the head buildup divided by discharge in the injection well is far in excess of the predicted values. Plots of the values for tests 2 and 3 gave similar results, but the excess head buildup in IW-2 and ASW became greater with successive tests.

EXCESS HEAD BUILDUP DUE TO HYDRAULIC CONDUCTIVITY DETERIORATION

The field data indicate that only a part of the excess head buildup can be explained by temperature and density differences. The balance must be associated either with hydraulic conductivity deterioration in the aquifer or with entrance losses due to clogging of the screen and gravel pack. As a first approach to estimating hydraulic conductivity alteration due to clay dispersion, equation 5 may be solved for K_{1c}, the hydraulic conductivity of the aquifer to the injected water, and observed head differences may be inserted in place of the expression

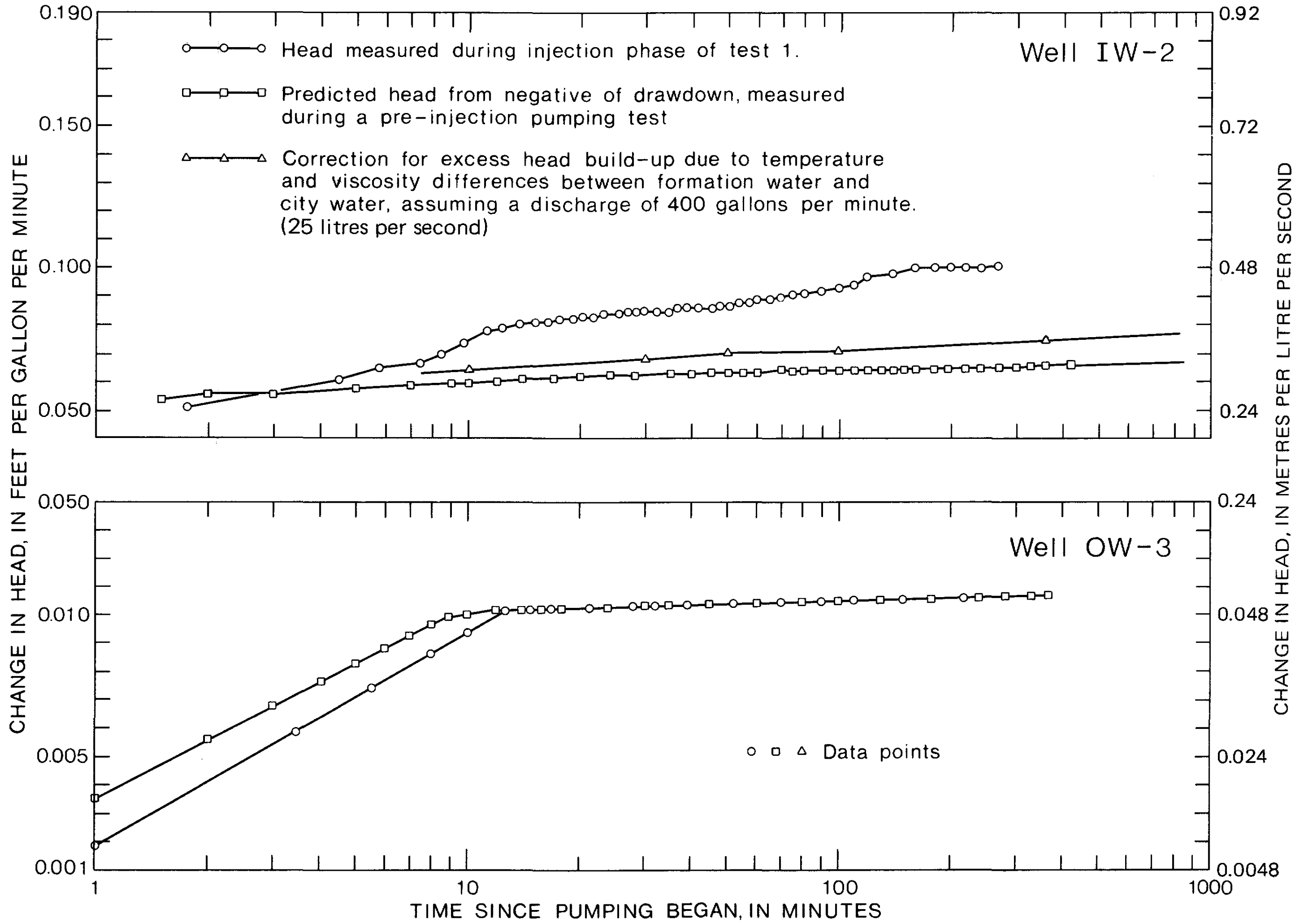


FIGURE 10.—Theoretical and measured head data for injection well IW-2 and observation well OW-3, test 1.

(S_{wTt}-S_{wt}). That is, the difference between the head buildup actually measured during an injection test and the theoretical head buildup taken from the drawdown measured during pumping at an equal rate may be substituted for (S_{wTt}-S_{wt}). This yields the equation:

$$K_{1c}=\frac{\frac{2.3Q}{2\pi D}\left(\log\frac{r_i(t)}{r_w}\right)(K_1)}{K_1\ (S_{inj}\ -S_p)+\frac{2.3Q}{2\pi D}\log\frac{r_i(t)}{r_w}}\ , \qquad (6)$$

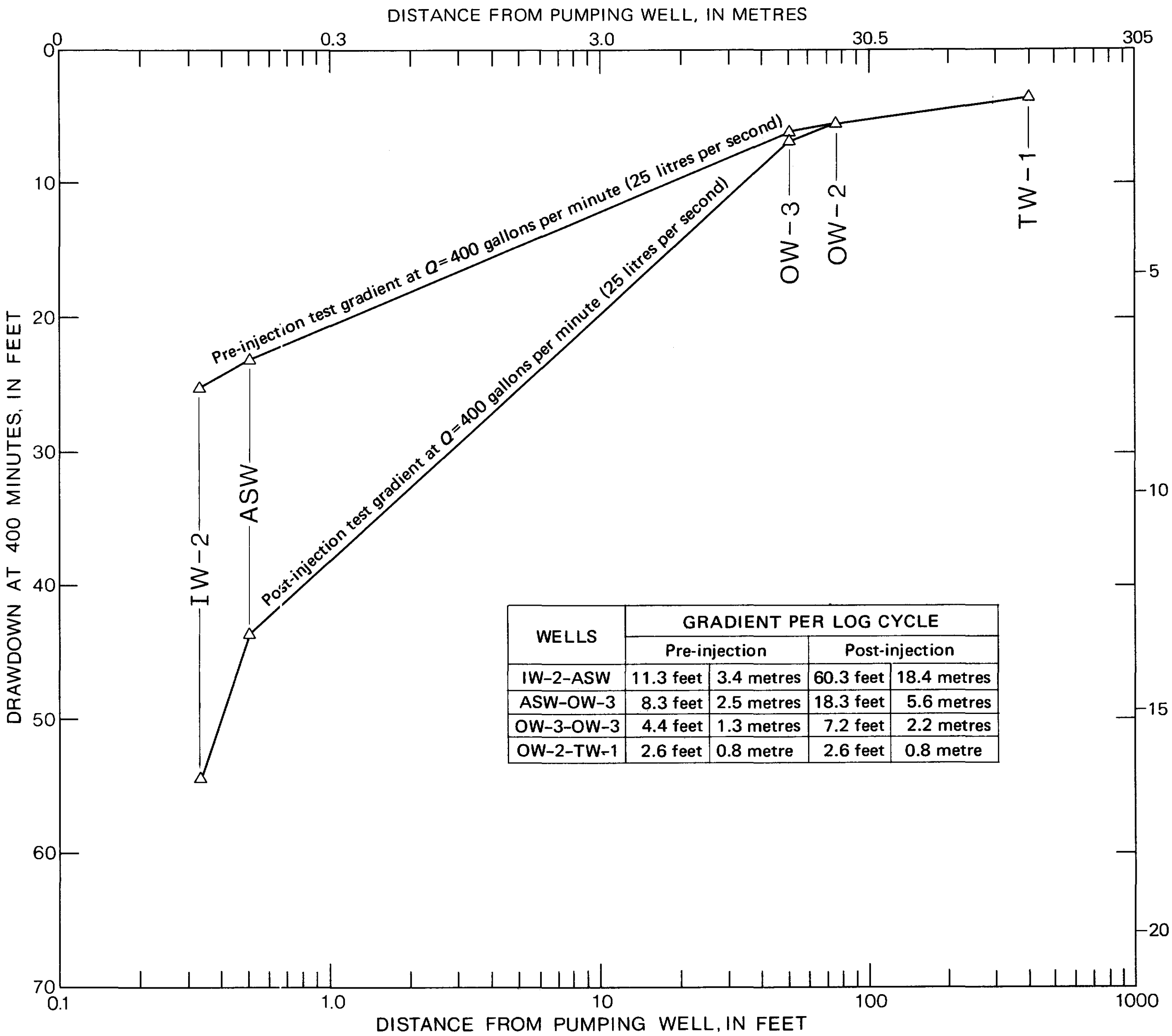
where S_{inj} =the head buildup measured after a time (t) of injection at the rate (Q);

S_p =the drawdown measured after the same time during pumping at a rate (Q), prior to any injection;

and the remaining terms are as previously defined. If no alteration has occurred in the aquifer and if entrance losses are negligible, equation 6 should yield a hydraulic conductivity equal to that calculated for the injection water from the relation $K_{1c}=K_1(u/u_c)$. Deterioration of the aquifer's hydraulic properties should be indicated by a lower hydraulic conductivity value. This approach assumes all excess head to be due to hydraulic conductivity deterioration rather than to clogging of the screen.

Application of equation 6 at several different time values during injection test 1 yielded a hydraulic conductivity of about half that calculated from the relation $K_{1c}=K_1\ (u/u_c)$. Application of the equation in later tests yielded even lower hydraulic conductivity values, but it is believed that these later results may reflect the results of screen clogging as well as hydraulic conductivity deterioration.

Figure 11 shows distance-drawdown plots from two aquifer tests—one prior to any injection, and one following test 3, after removal of all injection water and extensive redevelopment to remove screen-clogging particles. Both tests were made at a discharge rate of 400 gal/min (25 l/s). Calculation by the distance-drawdown method using the gradient between ASW and OW-3 shows that the average lateral hydraulic conductivity following the three injection tests was about 50 percent of the original value. The value agrees with the estimates obtained from test 1 using equation 6. The fact that the redevelopment pumping did not restore the hydraulic conductivity to its original value illustrates the irreversible nature of the deterioration.



WELLS	GRADIENT PER LOG CYCLE			
	Pre-injection		Post-injection	
IW-2-ASW	11.3 feet	3.4 metres	60.3 feet	18.4 metres
ASW-OW-3	8.3 feet	2.5 metres	18.3 feet	5.6 metres
OW-3-OW-3	4.4 feet	1.3 metres	7.2 feet	2.2 metres
OW-2-TW-1	2.6 feet	0.8 metre	2.6 feet	0.8 metre

FIGURE 11.—Pre-injection and post-injection hydraulic gradients.

Figure 11 shows that after injection of freshwater, the hydraulic gradient steepened greatly near the pumping well and has, in fact, been modified as far as 50 ft (15 m) from the pumping well. The hydraulic gradient steepened between OW-3 and OW-2 but not between OW-2 and TW-1. This is because freshwater was injected slightly beyond the radius of OW-3 but not as far as OW-2. Everywhere that the freshwater displaced the brackish water, deterioration of the aquifer hydraulic conductivity occurred. It can be shown, by plotting head buildup versus distance for each injection test, that the deterioration becomes more severe with each test and does not improve significantly with development pumping. The greatest amount of deterioration, as would be expected, is close to the injection well.

CURRENT-METER TRAVERSES

Figure 12 shows the flow pattern of water entering the screen during test 1 and the flow pattern during pumping before any injection tests. Minor clogging occurred in two zones; 917 to 923 ft (280 to 281 m) and 951 to 961 ft (290 to 293 m) below sea level. A decrease in flow of 14 percent in the upper zone and 15 percent in the lower zone is believed to have resulted from clogging of the injection sand by particulate matter. Agitation of the drilling mud, silt, and sand in the fill-up pipe or movement of drilling mud not removed from the filter pack by development may have been the source of the material. During the withdrawal phase, the clogged zones became productive again, and the flow pattern reverted to the pre-injection condition (fig. 13).

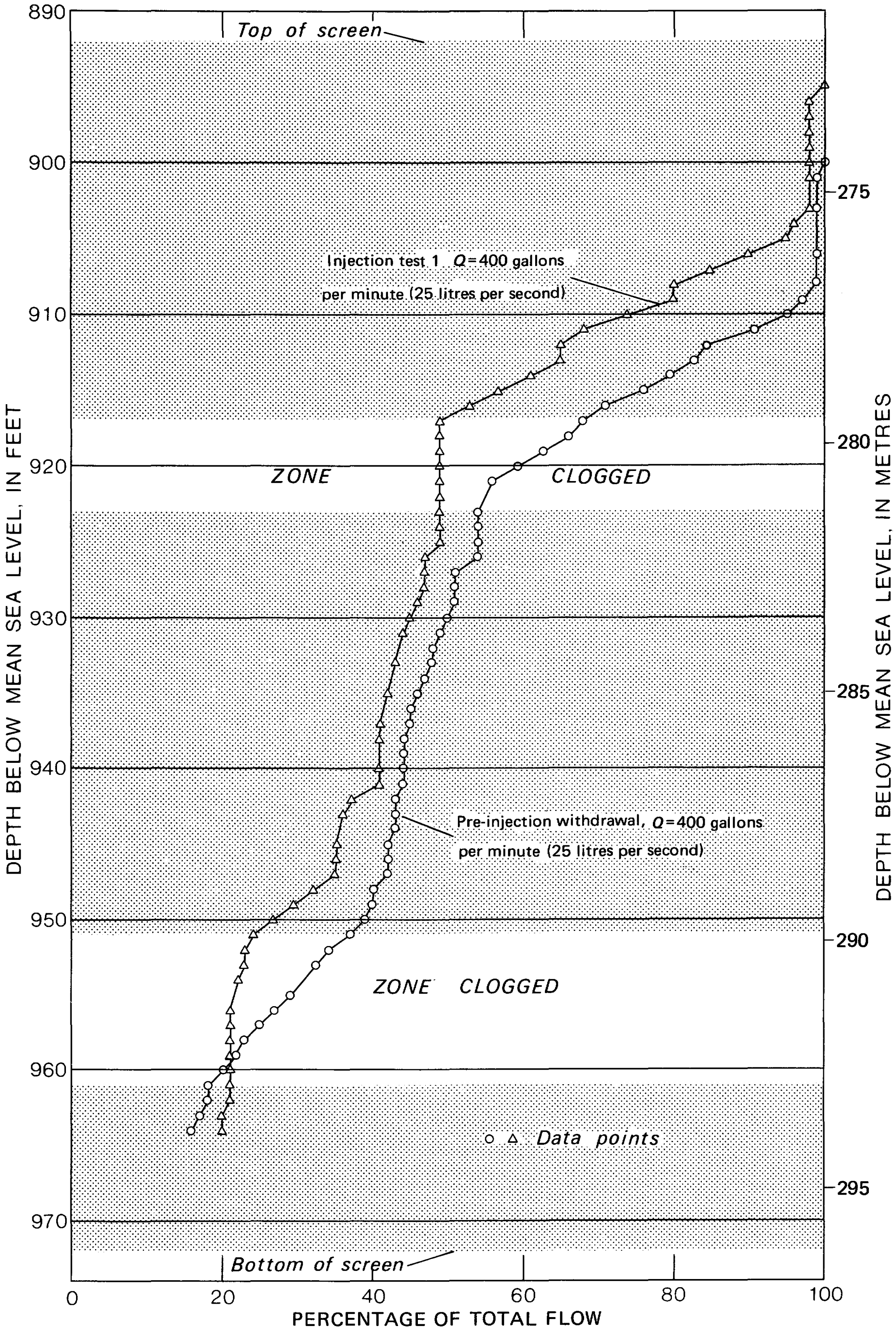


FIGURE 12.—Current-meter traverses in injection well IW-2 of the pre-injection flow and the flow after 5 hours of injection during test 1.

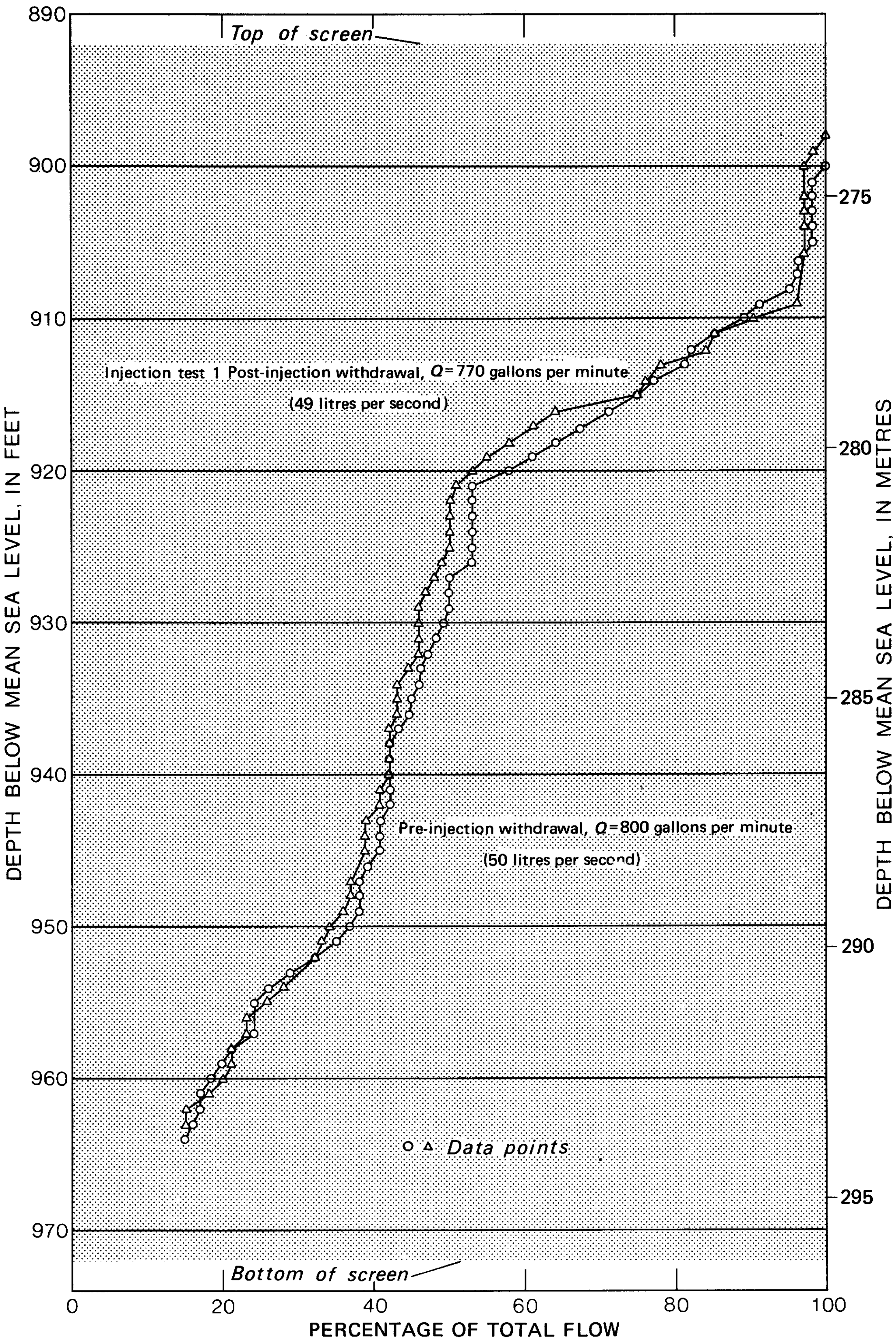


FIGURE 13.—Current-meter traverses in injection well IW-2 of the pre-injection flow and the withdrawal flow during test 1.

During injection test 2, the flow pattern deviated from that determined by pre-injection tests (fig. 14). The change was not so much in the minor zones that clogged, but rather in a new zone that developed and began taking water. The sand from 898 to 906 ft (274 to 276 m) below sea level took nearly 20 percent of the total flow by the end of 24 hours of injecting.

In all the pre-injection test 1 traverses, the sand zone from 897 to 917 ft (273 to 280 m) below sea level contributed virtually no water from the aquifer. In tests 1, 2, and 3, but especially in test 2, as pressure became greater in the injection well and sand zones began clogging, the 897- to 917-ft (273- to 280-m) zone began taking water. In test 2, this zone began taking water after 35 minutes of injection and continued taking water in the lower part for the remainder of the test. The lower part of the sand zone contributed water during the withdrawal phase of test 2 and remained open throughout test 3.

Examination of the drill cuttings and geophysical logs indicates that the sand zone from 897 to 917 ft (273 to 280 m) is clean, moderately sorted, porous, and permeable and should have contributed water since the initial development of the well. Probable causes for the lack of contribution from this zone are either clogging by drilling mud that was not removed from the gravel pack during development or by cement implaced during the construction of the well.

Evidence that drilling mud remained in the gravel pack consists of glauconite grains and Miocene microfossils recovered in the turbid water pumped during the withdrawal phase of test 2. Both items are foreign to the injection zone. The pH data observed prior to any injection tests present strong evidence supporting the theory of cement influence of water in IW–2. Injection well 2 was completed in May 1970 and was not pumped between May 1970 and July 1971. Water samples gathered by a thief sampler in December 1970 had a pH of 11.7 compared with a normal formation water pH of 7.8. During subsequent test pumpings over a period of several months, the pH was never above 7.8 even when the well was idle for as long as a month. These facts indicate that the cement reaction had gone to completion before injection test 1 began.

Nine current-meter traverses were made in IW–2 during the injection phase of test 2 (fig. 15). It is significant to note that the plot of traverses 1 through 9 nearly parallel each other even though the injection rate decreased from a high of 400 gal/min (25 l/s) during traverse 1 to 240 gal/min (15 l/s) during traverse 9. If the reduction in the ability of the aquifer to accept the water was caused by physical clogging with particulate matter, the flow pattern could be expected to change with time. Clogging would be most severe in the zones initially accepting the most water; deterioration of these zones would then force flow into the less permeable zones. Figure 15 supports the alternate theory that the reduction in acceptance of water is due to rather uniform reduction in hydraulic conductivity of the entire screened interval.

Figures 16 and 17 illustrate the flow patterns during the withdrawal phase of test 2. The percentage of total flow from individual sections of the aquifer did not change appreciably with time, even though the flow increased from 575 to 670 gal/min (36 to 42 l/s). Traverse 6 (fig. 17) more nearly matches the pre-injection flow pattern than traverse 1 (fig. 16), probably because of the increased percentage of formation water being pumped. Base exchange again occurred as the brackish formation water replaced the injected water in the formation and increased the hydraulic conductivity, although not to its original value.

During injection in test 3, the flow pattern shows a drastic variation from those established during injection in tests 1 and 2 (fig. 18). The entire basal section of the aquifer, from 945 to 972 ft (288 to 296 m) below sea level, took less than 10 percent of the total recharge. In the pre-injection traverse, this same zone contributed about 32 percent of the total flow. Moreover, the zone from 923 to 945 ft (281 to 288 m) below sea level, which in the pre-injection traverse contributed only 10 percent of the total flow, took 41 percent of the flow. The flow at the time of the traverse was 70 gal/min (4.4 l/s). This plugging of selected zones and development of less permeable zones during injection conforms to the expected pattern of changes due to clogging by particulate matter.'

During test 3, the post-injection withdrawal flow pattern roughly parallels the pre-injection flow pattern. The reason the traverses do not match is that the lower section of the aquifer had failed to develop during the period of withdrawal pumping prior to making the screen traverse.

The injection current-meter traverse (fig. 18) could not be made until the injection rate stabilized. The initial 100 min of injection accounted for nearly all the decrease in the rate of injection (fig. 19). By the time the injection traverse was made, the acceptance rate of the formation had nearly stabilized; particle clogging had effectively reduced the input into the more permeable zones, forcing water to enter less permeable zones, and causing correspondingly higher injection heads.

The origin of this particulate clogging may have been fine material that accumulated at the bottom of the well during the extensive redevelopment pumping following test 2. This material may have been agitated into suspension at the start of injection in test 3 and lodged in the screen and gravel pack. Another explanation might be that material from horizons above the screen sifted downward through breaches in the gravel pack around the screen, causing some choking of the upper part of the screen.

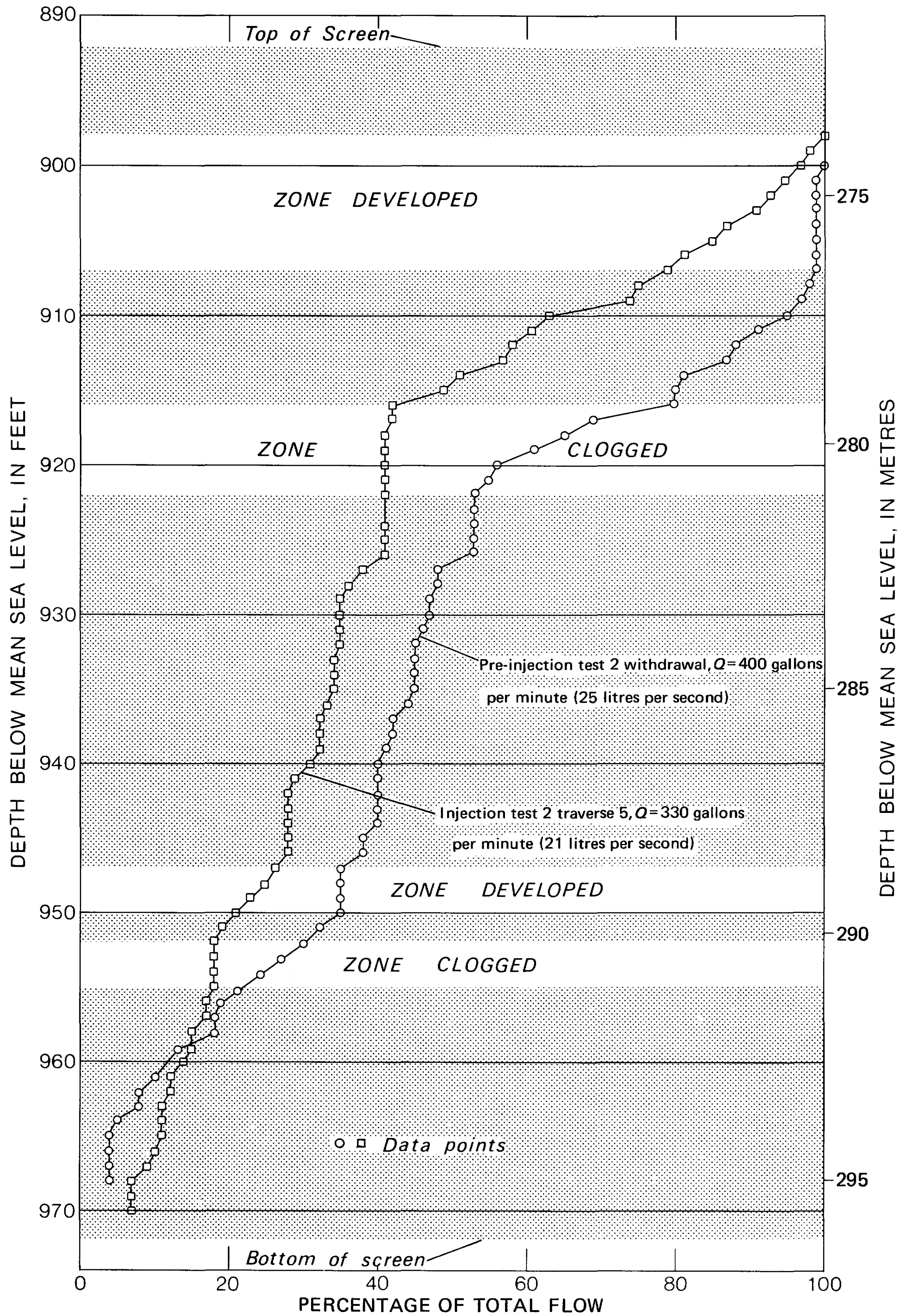
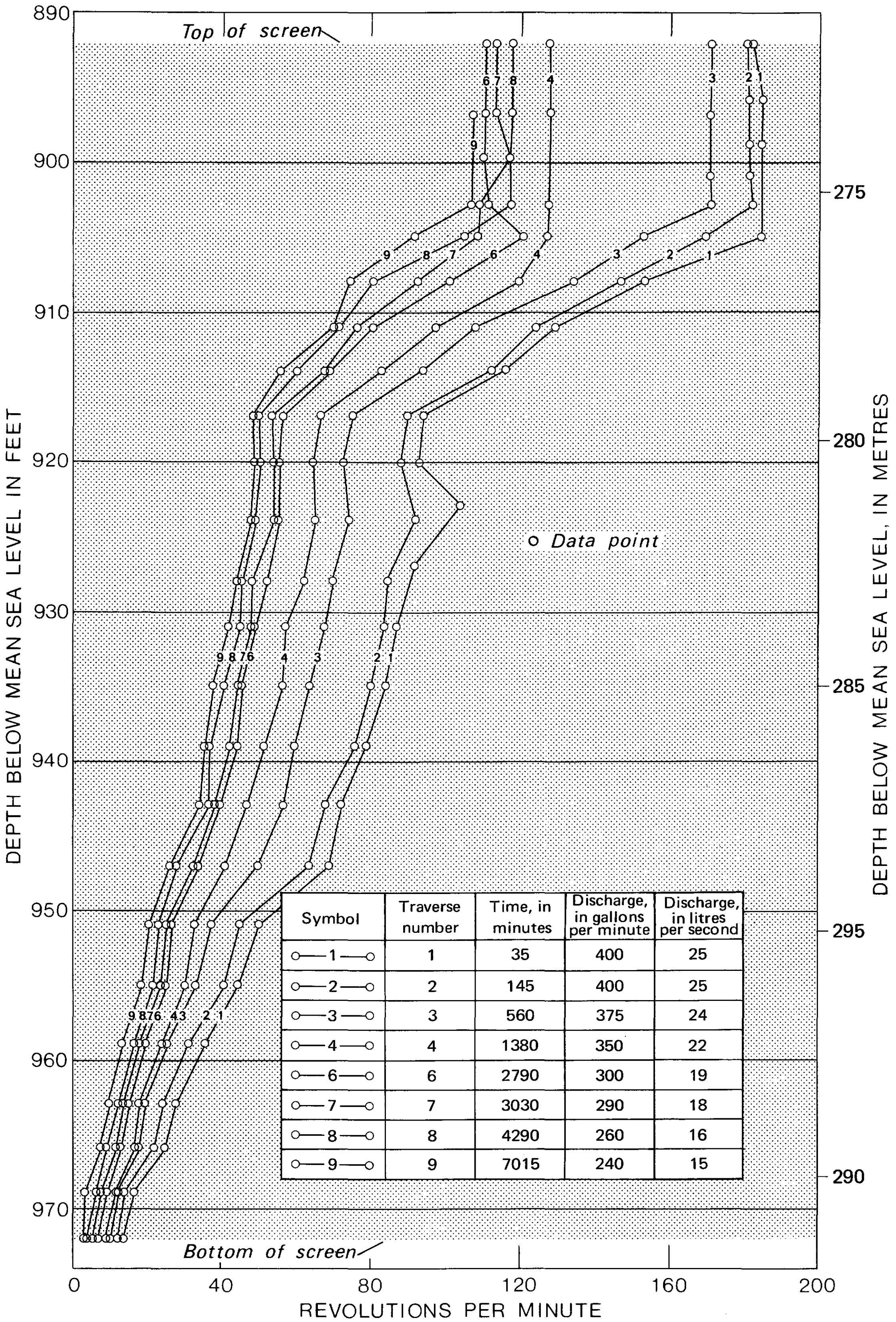


FIGURE 14.—Current-meter traverses in injection well IW-2 of the pre-injection flow, test 2, and the flow after 24 hours of injection during test 2.



Symbol	Traverse number	Time, in minutes	Discharge, in gallons per minute	Discharge, in litres per second
o—1—o	1	35	400	25
o—2—o	2	145	400	25
o—3—o	3	560	375	24
o—4—o	4	1380	350	22
o—6—o	6	2790	300	19
o—7—o	7	3030	290	18
o—8—o	8	4290	260	16
o—9—o	9	7015	240	15

FIGURE 15.—Current-meter traverses in injection well IW-2 during the injection phase, test 2.

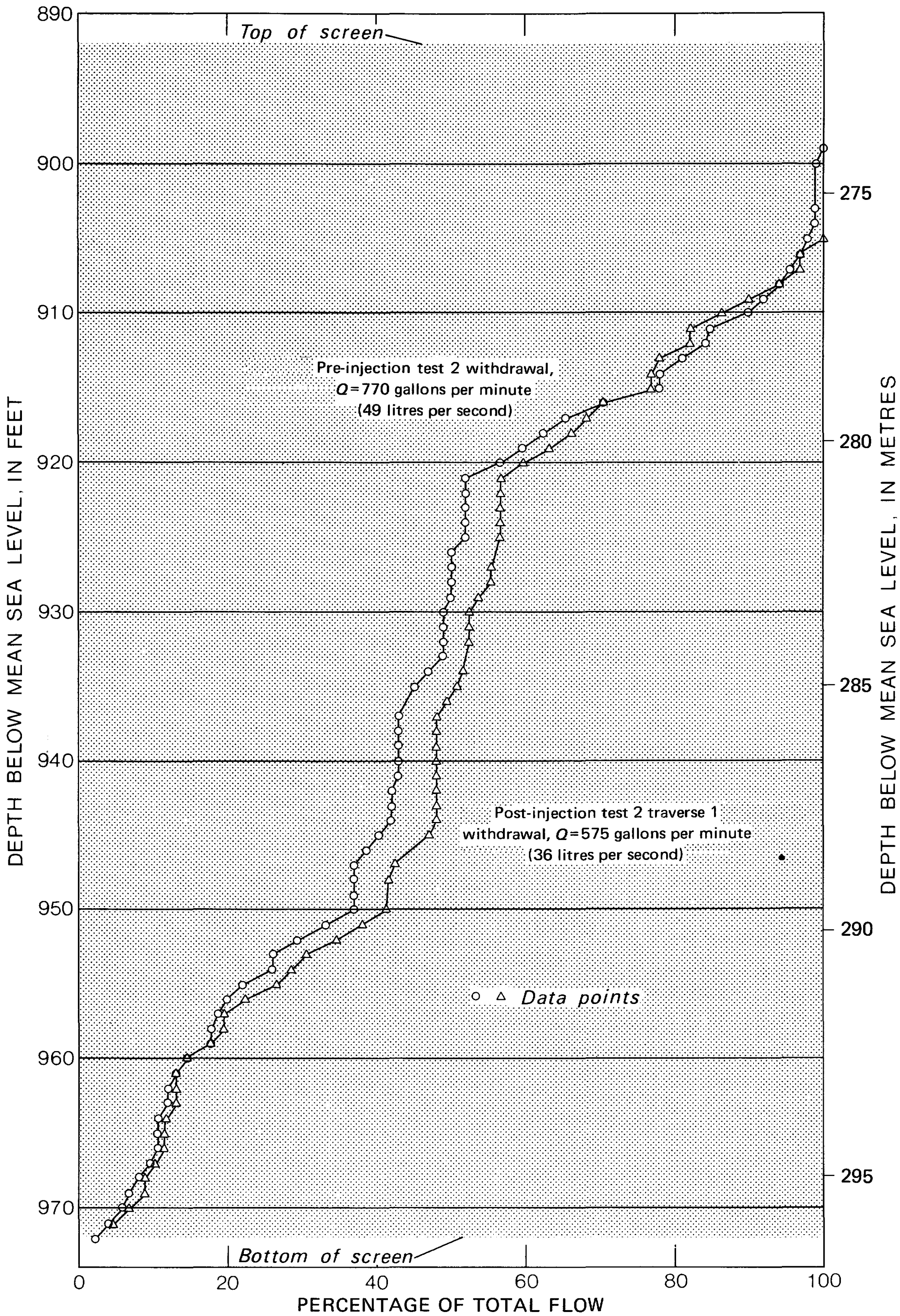


FIGURE 16.—Current-meter traverses in injection well IW-2 of the pre-injection flow, and the withdrawal flow, test 2.

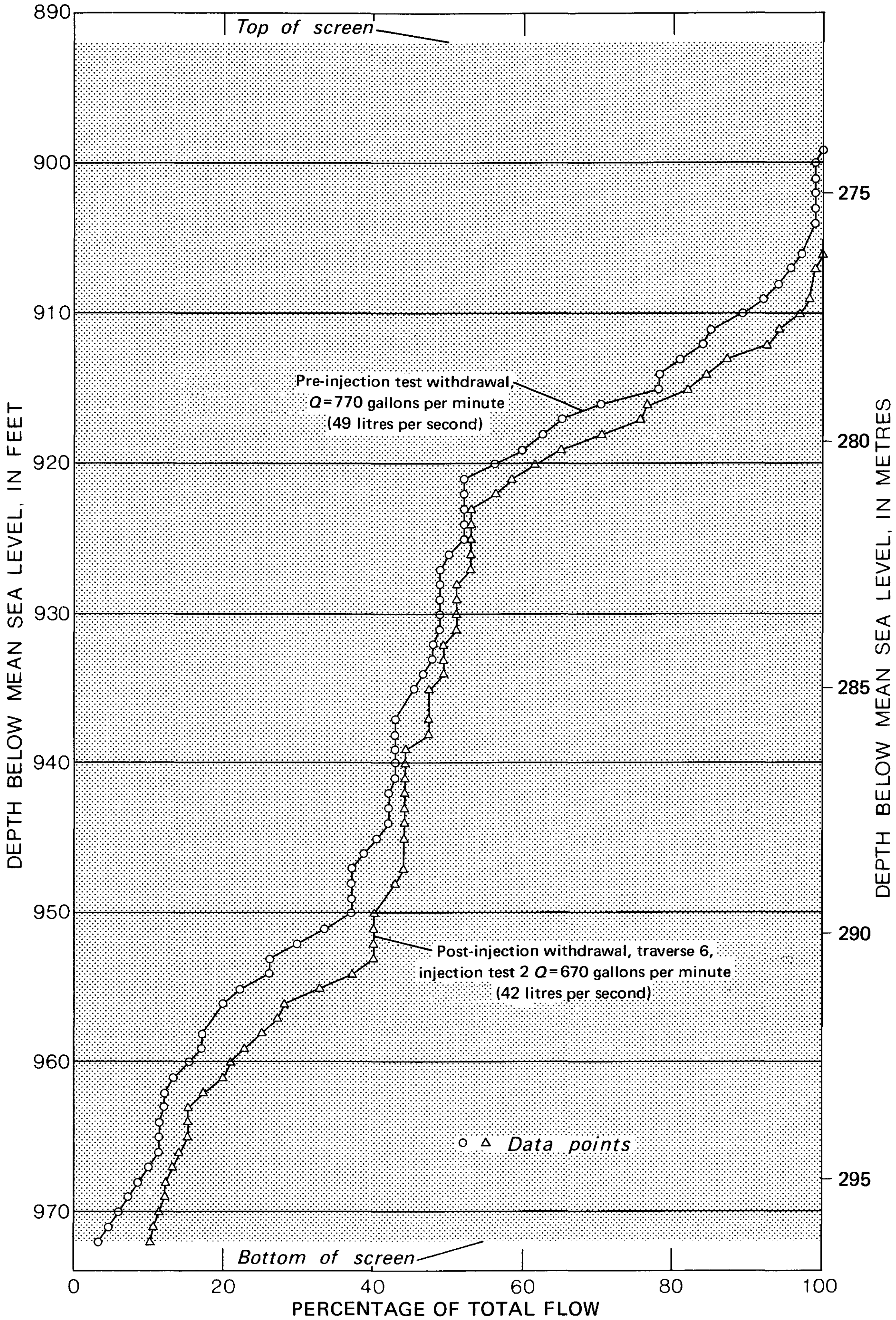


FIGURE 17.—Current-meter traverses in injection well IW-2 of the pre-injection flow, test 2, and the flow after 75 hours of withdrawal pumping during test 2.

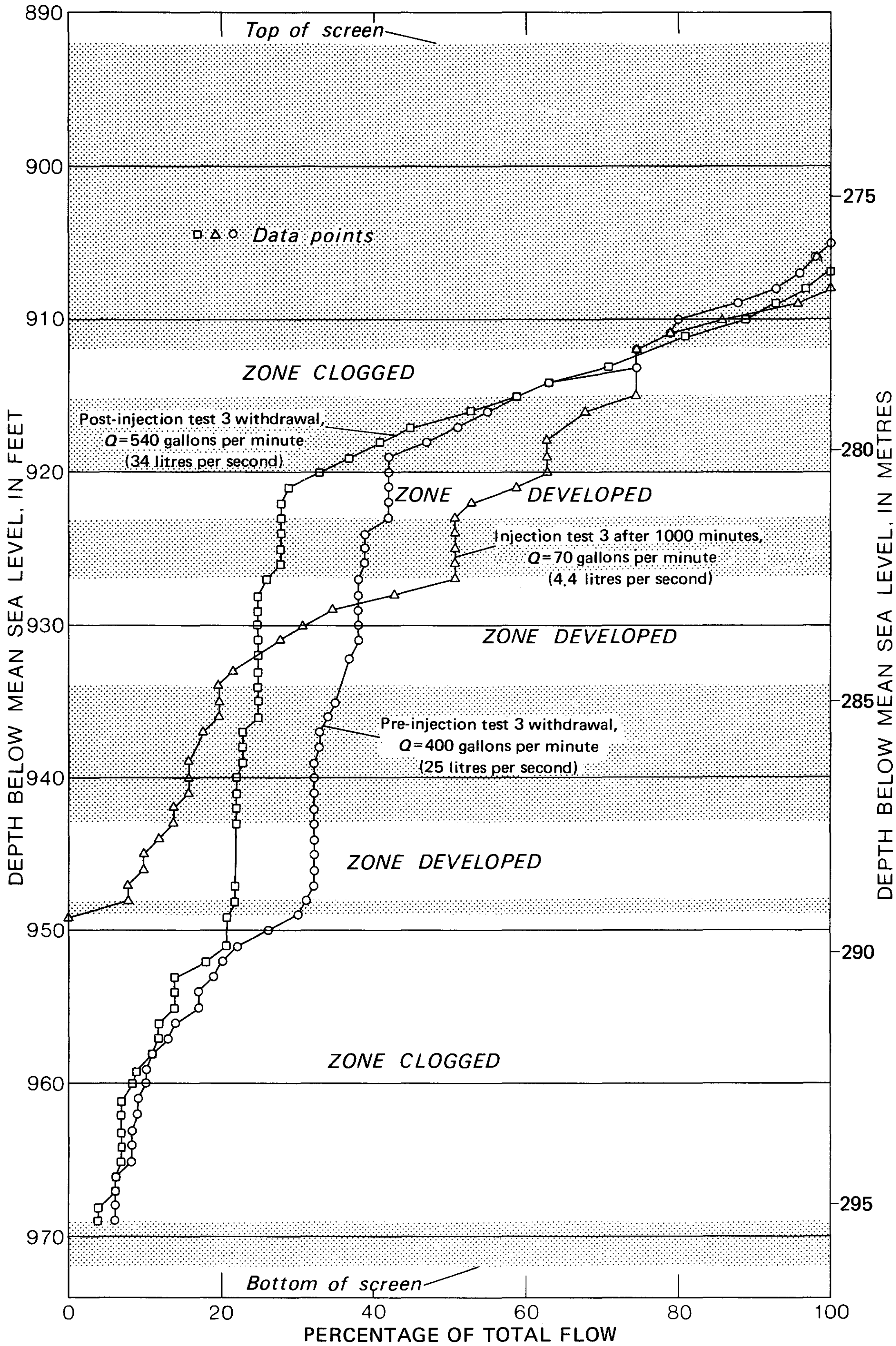


FIGURE 18.—Current-meter traverses in injection well IW-2 of the pre-injection, injection, and withdrawal flows, test 3.

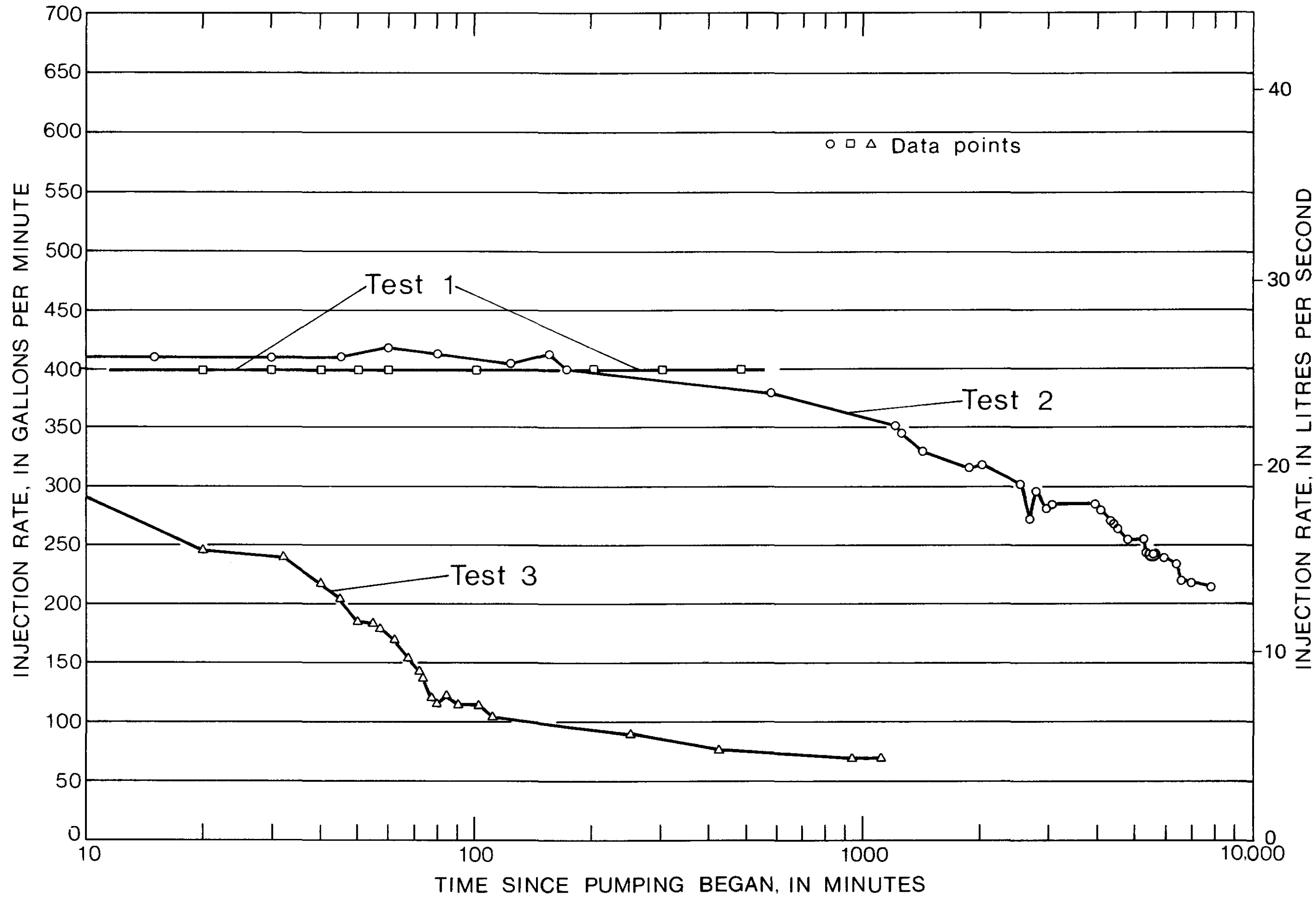


FIGURE 19.—Changes in injection rate with time during tests 1, 2, and 3.

SPECIFIC CAPACITY

Figure 20 shows the change of injection specific capacity with time (see table 6). It illustrates, as did the decline in injection rate, the progressive deterioration of the aquifer hydraulic conductivity with successive tests. Neither development nor withdrawal pumping returned the specific capacity of the well to pre-test levels, indicating permanent deterioration of the aquifer properties. Moreover, after the first few minutes, decline in specific capacity during injection continued at nearly the same rate as established in the previous injection test. Figure 20 shows that a definite departure from the pre-injection specific capacity pattern occurred in all three injection tests. The test 2 line falls between test 1 and the pre-injection line rather than between the lines for tests 1 and 3 because the head values for the annular-space well (ASW) had to be used rather than those of the injection well due to failure of the transducers in IW–2. The slope of the line is valid, however. Figure 20 suggests that if additional injection tests were made under the same conditions as the previous tests, further deterioration of the specific capacity of the well could be expected.

CONDUCTIVITY SURVEYS

During the injection phase of test 1 and the injection and withdrawal phases of test 2, conductivity traverses were made in the screen of OW–3 using a downhole probe to detect the arrival and movement of freshwater. The background conductivity along the traverse in OW–3 was 4,800 micromhos on a scale of 0 to 6,000. Changes of 50 micromhos were considered significant. No apparent freshening of the water in OW–3 occurred during test 1. The first definite detection of freshwater in OW–3 was during test 2 after 5,433 min (3.77 days) of injection (fig. 21). Approximately 1.8 Mgal (6,800 m^3) of freshwater had been injected at that time. The freshwater first appeared at the depth interval of 895 to 899 ft (273 to 274 m) below sea level, near the top of the injection zone.

Figure 21 indicates that there may have been some internal flow within OW–3 during the injection test caused by small vertical head differences in the aquifer; uncertainty regarding such internal movement complicates the interpretation of the breakthrough curves. Nevertheless, there appear to be two additional zones in which breakthrough of freshwater occurred as the

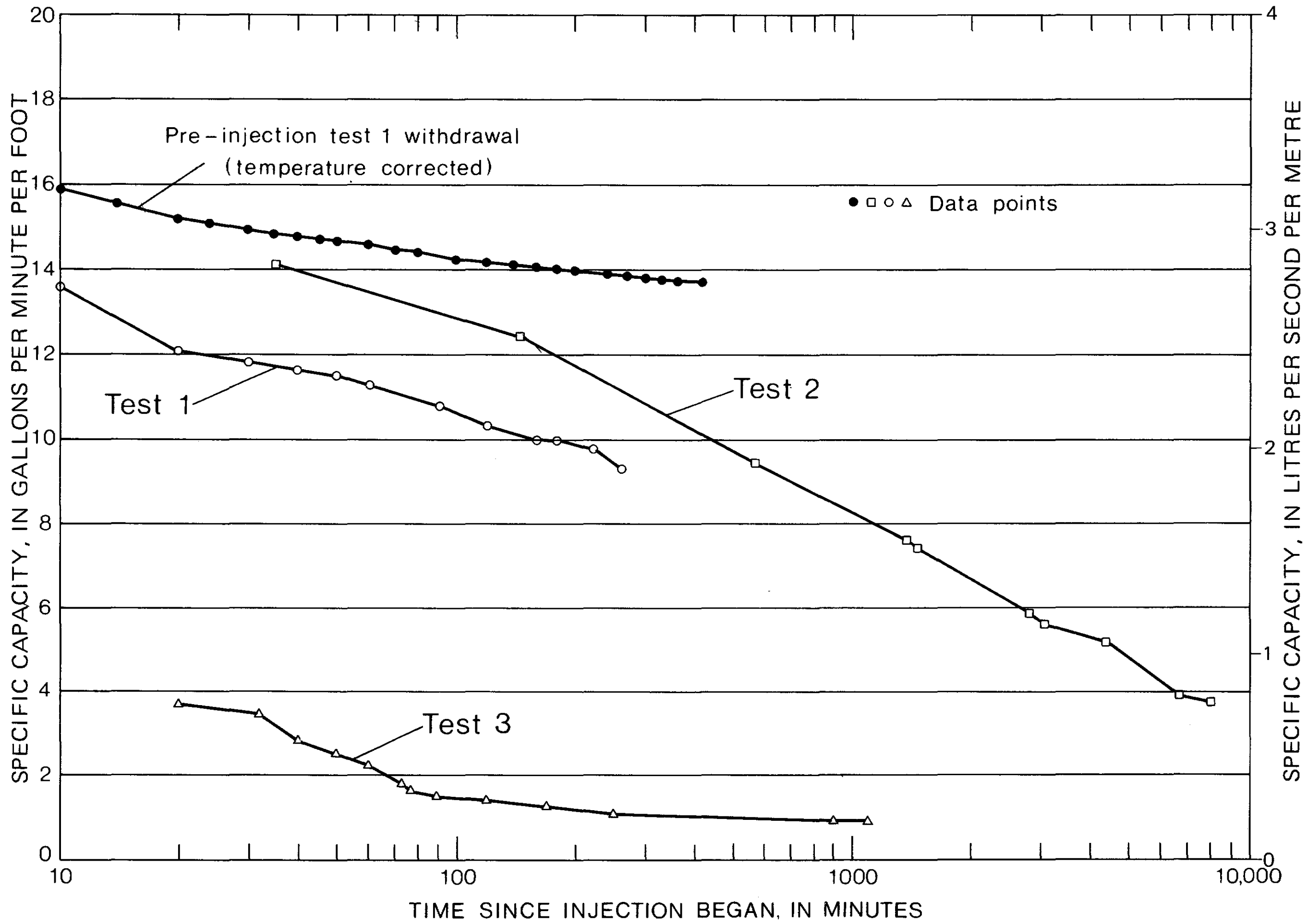


FIGURE 20.—Pre-injection withdrawal specific capacity of injection well IW-2 and injection specific capacity during tests 1, 2, and 3.

injection continued. The zones are from 908 to 916 ft (277 to 279 m) and 932 to 941 ft (284 to 287 m) below sea level. Figure 22 illustrates that the section of the aquifer taking 57 percent of the total flow in IW-2 is the same interval in which the dominant freshwater breakthrough occurred in OW-3. No apparent freshening of the water in OW-2, 75 ft (23 m) from the injection well, occurred during test 2.

During injection test 4, which will be described in a subsequent section, conductivity surveys were made in both OW-3 and OW-2 (figs. 23 and 24). Freshwater was detected in OW-3 after 1.82 Mgal (6,890 m^3) had been injected, virtually the same volume as was injected during test 2. The freshwater was again detected in virtually the same intervals as in test 2, indicating that the flow pattern between the injection well and OW-3 was repeatable. Freshwater was detected in OW-2 after 6.67 Mgal (25,250 m^3) of freshwater had been injected in IW-2.

Figure 25 is a lithologic section of a part of the well field showing the zones taking water in the injection well during injection test 4 and the zones of detection in the nearby observation wells. It demonstrates the continuity of sand lenses within the injection zone. The clay and silt beds from about 880 to 890 ft (268 to 271 m) and 975 to 985 ft (297 to 300 m) below sea level in OW-2 are the confining beds of the aquifer.

There is good correlation between the intervals of high input in the injection well and the intervals of freshwater breakthrough in the observation wells, suggesting that the flow occurred in a virtually horizontal pattern.

If it is assumed that the injection front moves outward in the aquifer in the form of a cylinder, the radius of the freshwater zone, neglecting hydrodynamic dispersion, is given at any time by the equation:

$$r_i(t)=\sqrt{\frac{V}{\pi m\theta}}, \tag{7}$$

where V=volume of water that has been injected up to time t, in cubic feet;
m=thickness of aquifer, in feet;
θ=porosity.

Equation 7 is equivalent to equation 3 except that r_w is considered to be negligible, V is used in place of

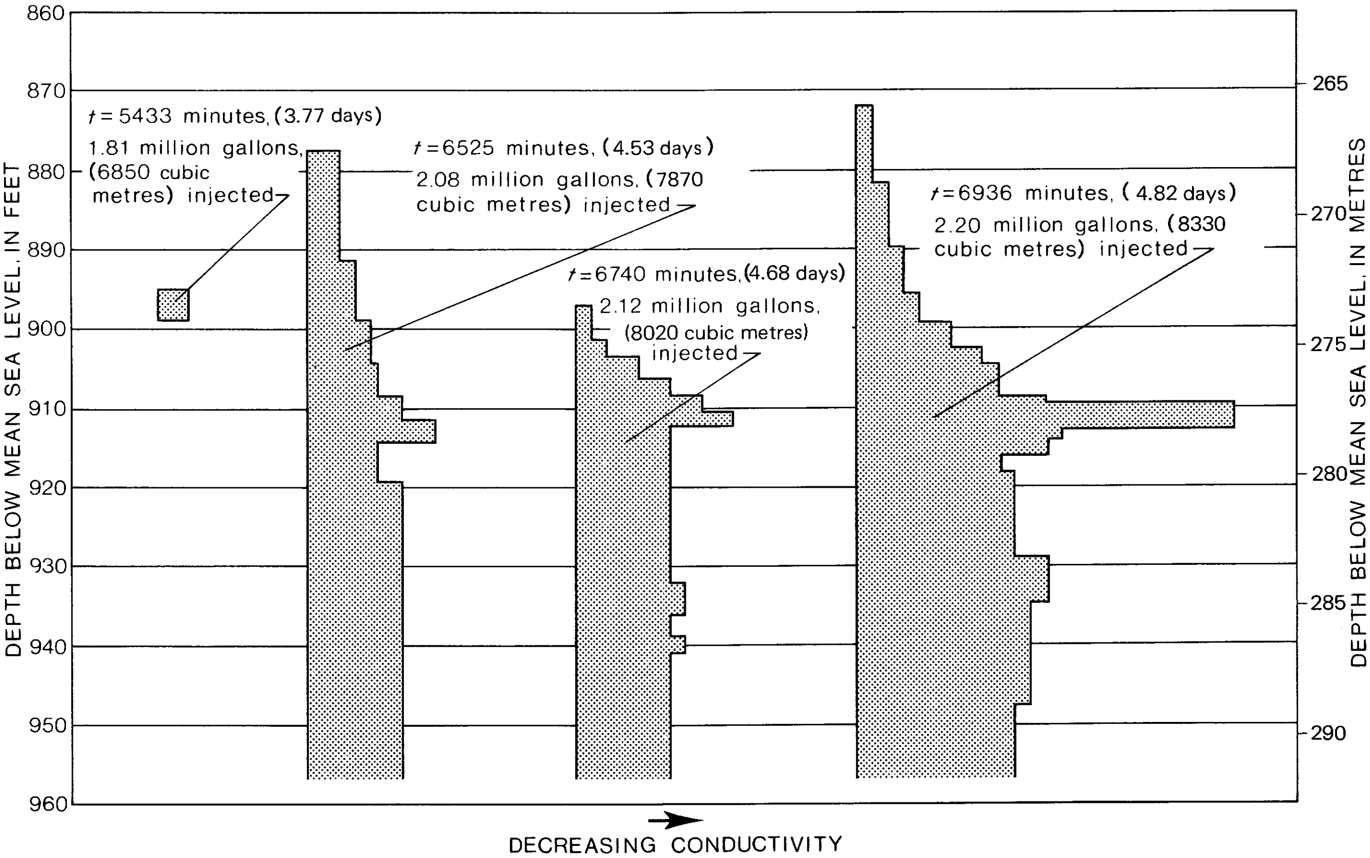


FIGURE 21.—Conductivity profiles in observation well OW-3 during injection phase, test 2.

TABLE 6.—*Specific capacity of injection well IW-2 during the injection phase of tests 1, 2, and 3*

Injection rate (gal/min)	Time since injection began (min)	Water-level change in IW=2 (ft)	Specific capacity (gal min⁻¹ft⁻¹)
	Injection Test 1		
400	6	26.0	15.4
400	10	29.5	13.6
400	20	33.1	12.1
400	30	33.9	11.8
400	40	34.5	11.6
400	50	34.8	11.5
400	60	35.5	11.3
400	90	37.0	10.8
400	120	38.7	10.3
400	160	40.0	10.0
400	180	40.0	10.0
400	220	41.0	9.8
400	260	43.0	9.3
	Injection Test 2[1]		
400	35	28.1	14.2
400	145	32.0	12.5
375	560	39.5	9.5
335	1380	44.3	7.6
330	1440	44.6	7.4
295	2790	49.7	5.9
285	3030	50.6	5.6
270	4290	52.1	5.2
220	6681	55.9	3.9
215	7896	57.8	3.7

TABLE 6.—*Specific capacity of injection well IW-2 during the injection phase of tests 1, 2, and 3*—Continued

Injection rate (gal/min)	Time since injection began (min)	Water-level change in IW=2 (ft)	Specific capacity (gal min⁻¹ft⁻¹)
	Injection Test 3		
245	20	66.7	3.7
240	32	69.4	3.5
215	40	75.6	2.8
185	50	72.9	2.5
175	60	75.8	2.3
155	67	75.8	2.0
135	73	75.8	1.8
125	77	75.8	1.6
115	90	75.9	1.5
105	120	76.2	1.4
90	250	84.0	1.1
70	900	72.9	0.96
70	1020	75.9	0.92
70	1100	75.4	0.93

[1]Change in water level measured in ASW rather than in IW-2.

$Q(t-t_c)$, and it is recognized that the thickness of aquifer, *m*, accepting flow may differ from the screen length, *D*.

At the time of detection of freshwater in OW-3 during test 2, a total of 1,813,000 gal (6,860 m³) had been injected. Using equation 7 and this volume, expressed in cubic feet, and using m=80 ft (24 m), θ=0.30, $r_i(t)$ is calculated as 56.7

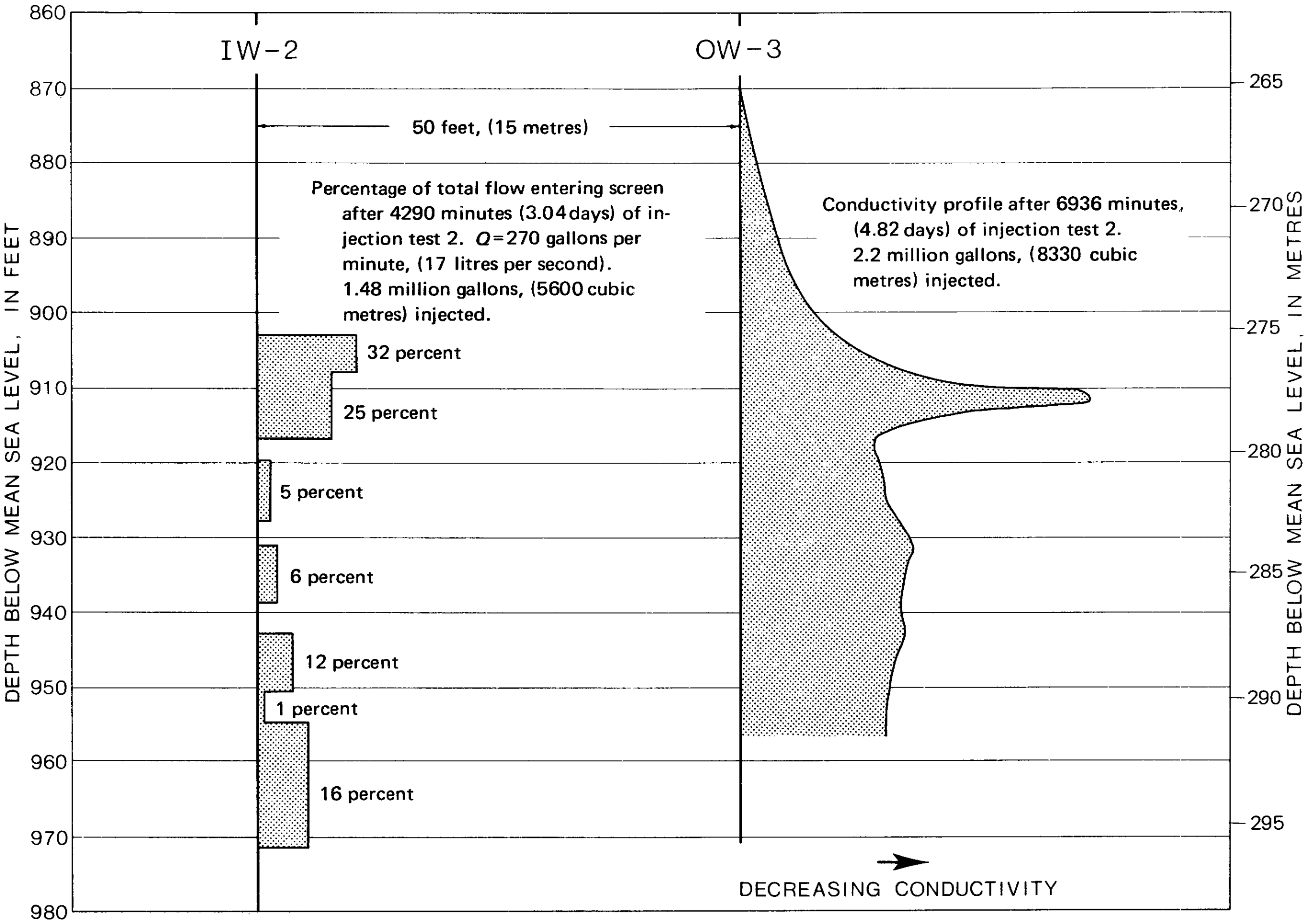


FIGURE 22.—Conductivity profiles in observation well OW-3 and current-meter traverse in injection well IW-2, test 2.

ft (17.3 m). However, the current-meter traverses show that only about 60 ft (18 m) of the injection-well screen was taking water; if m is taken as 60 ft (18 m) rather than 80 ft (24 m), $r_i\ (t)$ is calculated as 65.5 ft (20 m). Again, the current-meter traverses show that 40 percent of the total inflow occurred in the sand between 900 and 920 ft (274 to 280 m) below sea level, which correlates with the intervals of early breakthrough in OW-3. If equation 7 is solved using 40 percent of the injected volume and using m=20 ft (6 m), $r_i\ (t)$ is calculated to be about 72 ft (22 m). Thus, the injected water should have reached OW-3, at a distance of 50 ft (15 m) from the injection well, from 1 day to more than 2 days prior to actual detection, depending upon the assumptions used.

The calculations indicate that the injection front probably did not move out equally in all directions and form a cylinder. Subsequent calculations relating to the arrival time in OW-2, 75 ft (23 m) from the injection well, confirm this interpretation. A possible alternative is that the front may have had an elliptical form, as should be expected if the aquifer were homogeneous but anisotropic. However, comparison of the arrival times in OW-3 and OW-2 during test 4 rules out this possibility. It does seem clear, however, that the injection front was elongate in a direction roughly normal to the line through OW-2, OW-3, and the injection well. Trial calculations show that this elongation could not be due to superposition of a radial flow on the original hydraulic gradient in the aquifer, as this original gradient was very small.

AQUIFER HETEROGENEITY

A reasonable explanation of the arrival time data can be offered on the basis of the geology. The zone of greatest hydraulic conductivity in the upper part of the aquifer is probably a channel-fill or a shoestring sand. A deposit of this type would have the coarsest material along the center of the channel, with transition to progressively finer material along the sides. The average hydraulic conductivity across the channel would accordingly be lower than that along the channel axis, and injected water would tend to follow the channel axis. The channel would have a meandering orientation, but presumably its overall lineation would be at some angle to a line through OW-2, OW-3, and the injection well (IW-2). This interpretation

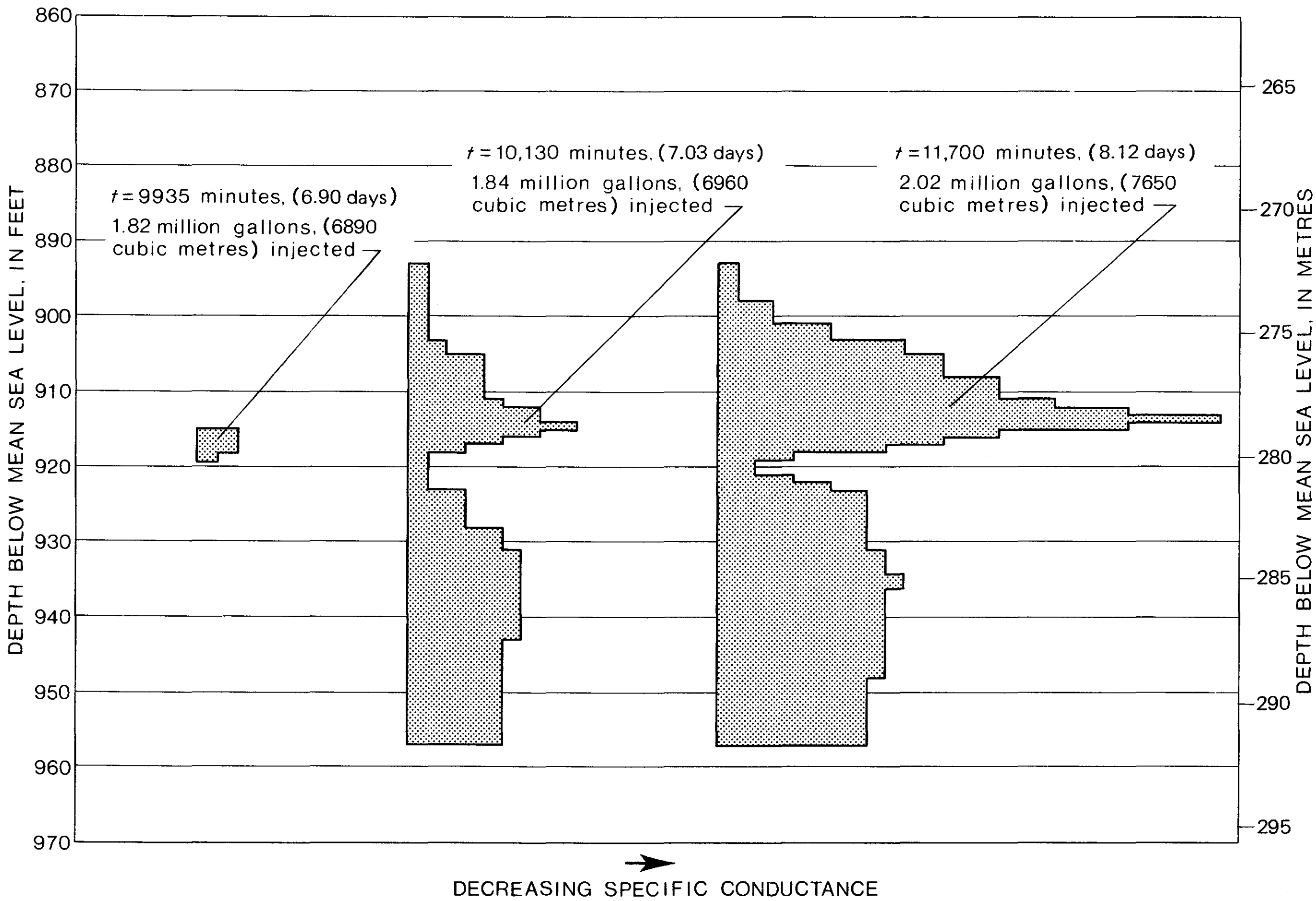


FIGURE 23.—Conductivity profiles in observation well OW-3, test 4.

is supported by aquifer-test data, which indicate that the specific capacities of wells IW-2 and TW-1 are higher than those of OW-3 and OW-2.

WATER QUALITY

COMPARISON OF THE CHEMISTRY OF CITY AND FORMATION WATER

The city water is a calcium sulfate chloride type, and the formation water is a sodium chloride bicarbonate type. The major constituents are listed in table 7. The dissolved-solids concentration of the city water varied between 110 and 190 mg/l, and the formation water contained about 3,000 mg/l.

WATER SAMPLING

Prior to injecting any freshwater into the host formation, consideration was given to the possibility of chemical reactions which might interfere with the injection process. For example, the freshwater to be injected was generally saturated with dissolved oxygen while the formation water contained none. Thus, if high concentrations of iron and manganese were present in the formation water, precipitation of iron or manganese hydroxides could occur within the formation when the freshwater was injected, resulting in loss of hydraulic conductivity of the aquifer. Chemical analysis, however,

TABLE 7.—*Concentration of major constituents from Moore's Bridges Filter Plant city water and formation water.*

[Values given in mg/l unless otherwise noted]

Constituents	Formation water	City water
Silica (SiO_2)	13	3.8
Calcium (Ca)	14	17
Magnesium (Mg)	8.7	2.6
Sodium (Na)	1,140	9.5
Potassium (K)	25	1.6
Bicarbonate (HCO_3)	624	9.0
Sulfate (SO_4)	136	36
Chloride (Cl)	1,360	21
Nitrate (NO_3)	.1	1.2
Phosphate (PO_4)	.28	.00
Boron (B)	3.4	.04
Fluoride (F)	1.4	.1
Dissolved solids	3,010	111
pH	7.9	5.8
Specific conductance (micromhos)	5,000	190

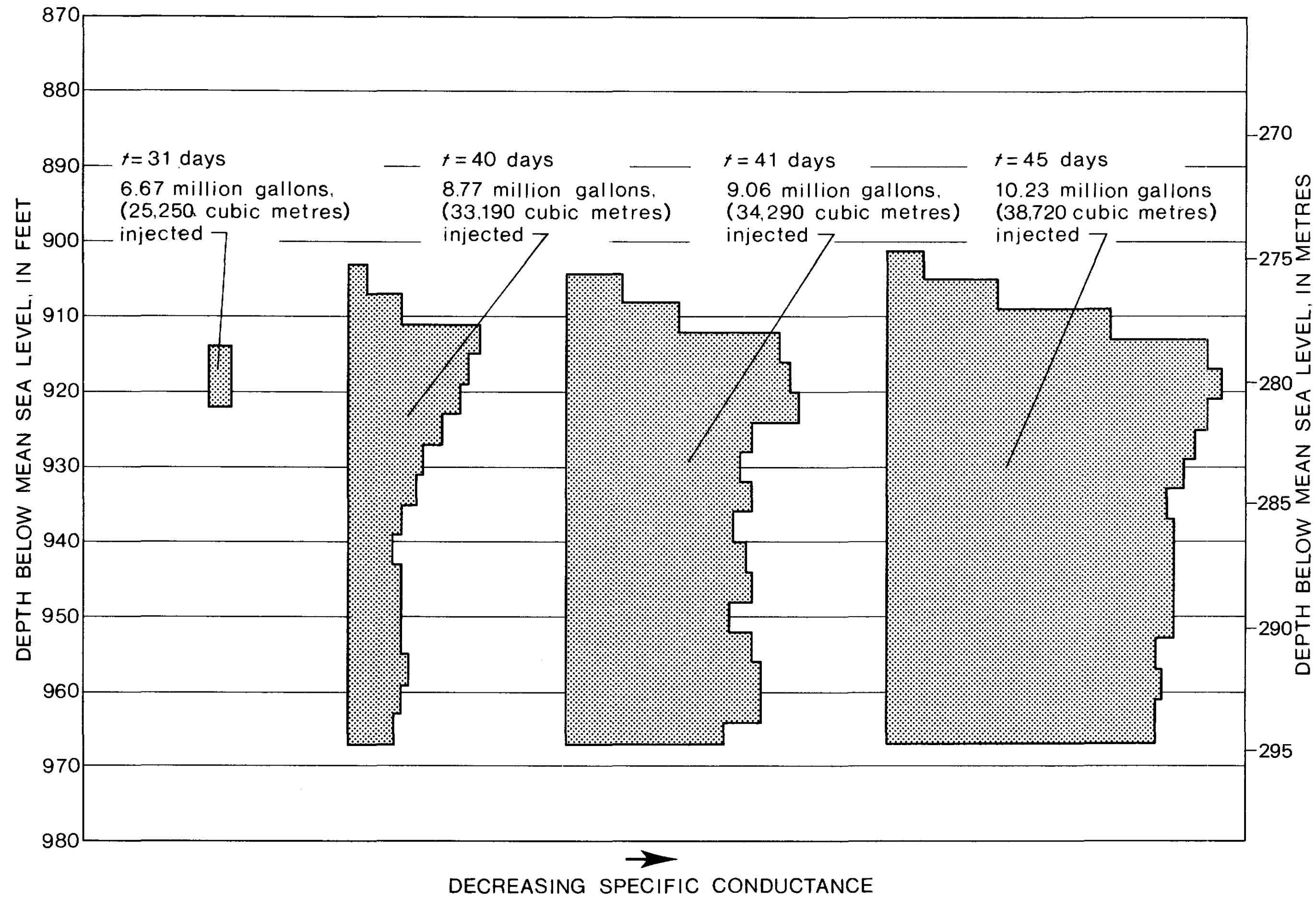


FIGURE 24.—Conductivity profiles in observation well OW-2, test 4.

indicated that the iron and manganese concentration in the formation water is too small (less than 0.1 mg/l to account for significant loss in hydraulic conductivity because of precipitation. Another possible chemical reaction was precipitation of calcium carbonate. However, studies carried out by Ivan Barnes (written commun., 1968) indicated that the concentration of calcium in both the freshwater and formation water was below equilibrium (saturation) values, and no precipitation would occur when the two waters mixed.

After examining the data, it was believed that when injection occurred, the major chemical effect would be simple dilution; in which case, three chemical zones would be formed around the wellbore. These include, in order of decreasing distance from the wellbore: (1) Undiluted formation water; (2) mixed formation and freshwater; and (3) freshwater. In order to chemically define these zones during the freshwater withdrawal phase, water samples were collected for chemical analysis whenever a change in specific conductance occurred (increase in specific conductance of 200 to 500 micromhos. The range in specific conductance was approximately 200 micromhos in freshwater to 5,000 micromhos in formation water. It was also believed that in collecting samples with respect to changes in specific conductance, the resulting chemical data would indicate not only when unsuspected reactions occurred, but also which constituents were involved. Unfortunately, as will be discussed later, some reactions took place when there was little or no change in specific conductance, and the withdrawn water was still virtually fresh.

ANALYTICAL RESULTS

It was previously stated that the formation water is predominately a sodium chloride type containing approximately 1,100 and 1,400 mg/l sodium and chloride, respectively. The freshwater contained 9.5 and 2.1 mg/l of sodium and chloride, respectively. It was assumed that as these two waters mixed a dilution would occur, and the analytical data as shown in table 8 tended to support this assumption. However, when these data concerning variations in the concentrations of sodium, chloride, and dissolved solids were plotted against specific conductance (fig. 26), the assumptions weakened. For example, the chloride values produced almost a straight-line relationship with respect to specific conductance, but sodium and

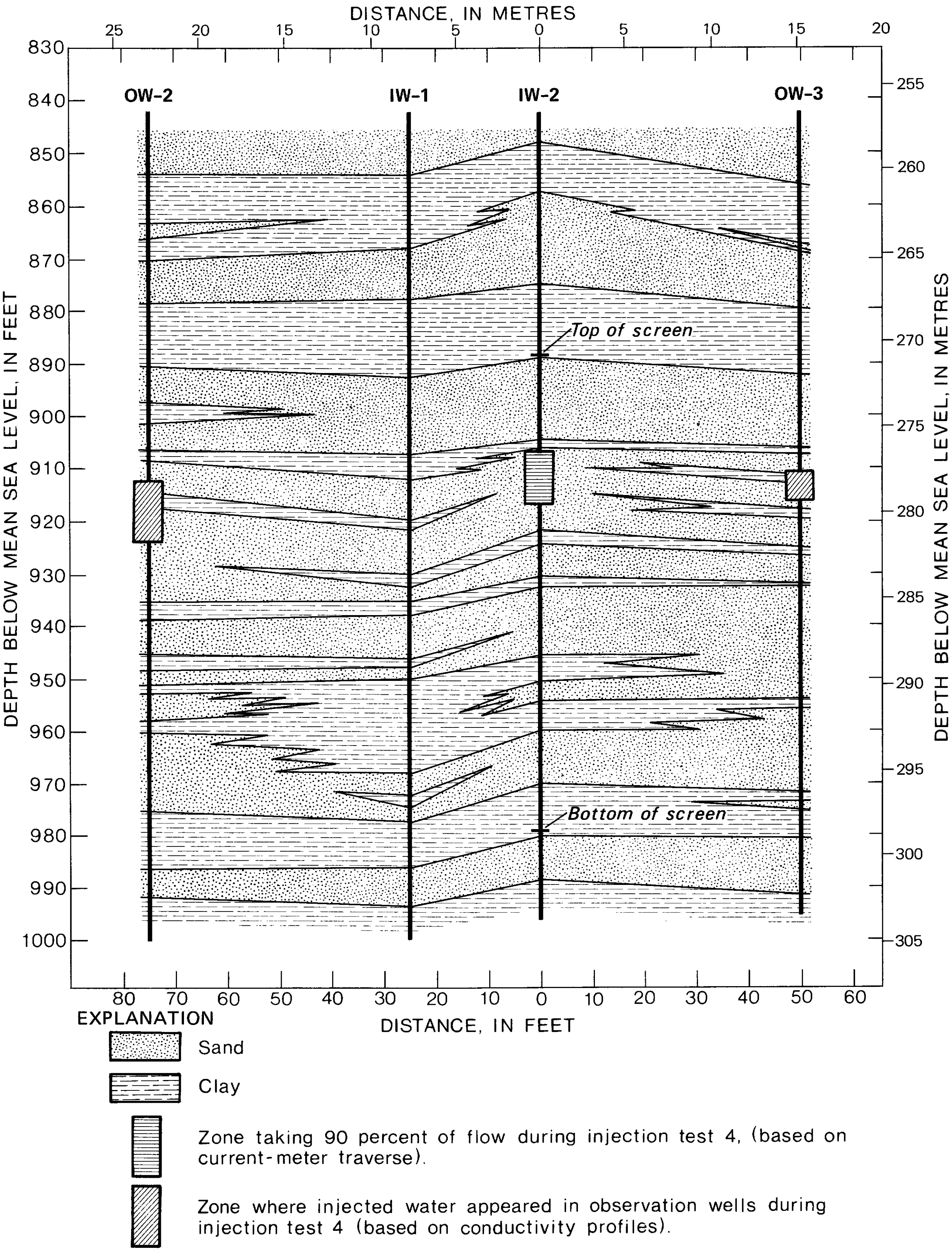


FIGURE 25.—Lithologic section showing injection zone in injection well IW-2 and zones of detection of freshwater in observation wells OW-2 and OW-3.

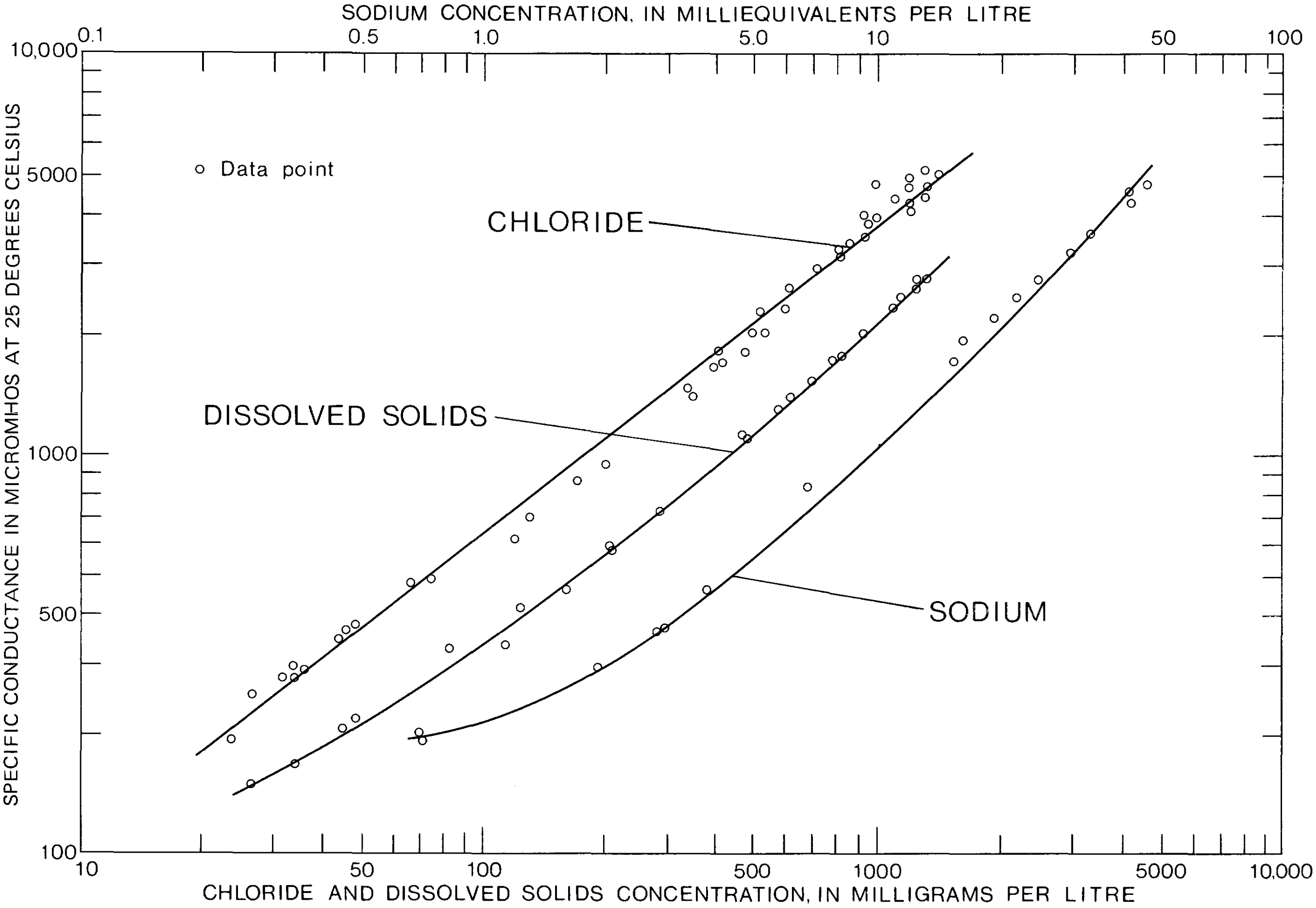


FIGURE 26.—Chloride, sodium, and dissolved solids versus specific conductance of recovered injected water from tests 1, 2, and 3.

the dissolved solids did not. Sodium and dissolved-solids concentrations tended to increase at a greater rate than changes in specific conductance or chloride, which indicated that sodium ions were being evolved by chemical reaction. The dilution concentration of other constituents, such as calcium and magnesium, indicated that there was little or no relationship between variations in concentration with respect to changes in specific conductance.

CHANGES IN THE CONCENTRATIONS OF CALCIUM, MAGNESIUM, AND SODIUM

The concentrations of calcium and magnesium in city water were 17 and 2.6 mg/l, respectively, and in formation water averaged 14 and 8.7 mg/l, respectively. The calcium and magnesium values in table 8 indicate that the concentrations of these two constituents in the mixed water were at times much lower or higher than their concentrations in either city or formation water. The water containing the low concentrations, however, was still virtually freshwater. During the later periods of withdrawal, when formation water became dominant in the mixture, the calcium and magnesium concentrations began to increase and were greater than could occur in a simple mixture. Near the end of withdrawal in test 1, the concentration of calcium was almost twice that in either city water or formation water. There appeared to be little doubt that calcium and magnesium were involved in some form of reaction as the freshwater entered the formation and that the reaction was reversible (fig. 27).

If calcium and magnesium concentrations were not decreasing as a result of calcite precipitation, then the decrease must have been due to simple cation exchange with the sodium-saturated clay within the formation. When calcium in the freshwater was exchanged onto the clay, exchangeable sodium from the clay should be released into the water. Thus, there should be an excess of sodium in the water when calcium concentrations approach minimum values. Figure 27 shows that calcium from the water was being lost (sorbed onto the clays) when the water was still fresh. As the percentage of formation water increased (based upon specific conductance), the calcium was exchanged from the clay into the water. Because of the small amount of sodium exchanged

TABLE 8.—*Variations in water chemistry of mixed freshwater and formation water during withdrawal, injection tests 1 and 2*

Specific conductance (micromhos)	Formation water (percent)	Calcium (mg/l)	Magnesium (mg/l)	Sodium (mg/l)	Potassium (mg/l)	Bicarbonate (mg/l)	Sulfate (mg/l)	Chloride (mg/l)
				Freshwater				
180	0.0	17	2.6	9.5	1.6	9	36	21
				Injection test 1				
290	1.0	6.2	2.0	48	8.4	60	34	35
370	2.0	4.0	2.1	72	8.8	73	35	49
840	11	8.0	2.3	160	13	129	45	170
2000	35	23	8.0	400	26	272	75	500
3400	61	31	12	710	35	422	100	860
4600	93	23	11	1000	40	582	130	1300
				Formation water				
5000	100	14	8.6	1200	40	618	150	1400
				Freshwater				
180	0.0	17	2.6	9.5	1.6	9	36	21
				Injection test 2				
190	0.3	10	3.2	17	2.9	8.0	36	24
245	.5	20	3.8	20	3.7	31	42	27
360	1.8	5.6	1.3	63	8.6	67	40	46
460	3.3	5.3	1.1	85	8.9	81	40	67
1400	14	10	2.5	220	13	256	52	220
1800	28	16	4.8	360	15	228	48	410
2300	36	16	5.5	460	17	274	66	520
2600	43	16	6.0	530	19	312	71	620
2900	51	17	6.4	590	21	352	74	720
3200	58	19	7.2	680	23	400	69	820
3800	68	24	8.8	800	25	456	81	960
4900	96	22	10	1000	29	620	63	1200
				Formation water				
5000	100	15	8.8	1100	29	608	69	1300

compared to the total in the water, the sodium data do not show clearly that there was excess sodium during the periods when calcium was being lost from the water. There is a slight change in the slope of the sodium curve (fig. 26) at low concentrations, indicating that the concentration of sodium was increasing at a greater rate than the specific conductance of the mixed waters.

An indirect technique to show that cation exchange was occurring was attempted based on the assumption that (1) chloride ions do not enter into any reactions during either the injection or withdrawal of the fresh water (fig. 26) and (2) sodium was involved in only the cation-exchange reaction. The ratio of sodium to chloride in city water is 0.71 and in formation water is 1.30. The ratios obtained from all the analytical data indicated that the sodium to chloride ratio was never less than 0.71, but was frequently more than 1.30. Furthermore, when the ratio was more than 1.30, the calcium concentration was much less than that of either the city or formation water, as shown in table 9. If a comparison is made between the calcium concentration data and the sodium to chloride ratios shown in figure 27, it can be seen that, with respect to specific conductance, excess sodium concentrations occurred

TABLE 9.—*Sodium to chloride ratio and associated concentrations of calcium in samples collected during injection tests 1 and 2.*

Specific conductance (micromhos)	Sodium-chloride ratio (meq/l)	Calcium (mg/l)
	Injection test 1	
290	2.11	6.2
370	2.27	4.0
840	1.45	8.0
2000	1.23	23
3400	1.27	31
4600	1.19	23
5000	1.30	14
	Injection test 2	
190	1.09	10
245	1.14	14
360	2.11	5.6
460	1.96	5.3
1380	1.54	10
1800	1.35	16
2300	1.36	16
2600	1.32	16
2900	1.26	17
3200	1.11	19
3800	1.29	24
4900	1.29	22
5000	1.30	15

during the withdrawal periods when calcium concentrations were approaching minimum values.

EFFECT OF CATION EXCHANGE ON FORMATION CLAY DURING INJECTION

It is unlikely that cation exchange during the injection phases had any effect except to slightly lower the zeta potential (tendency to disperse) of the clays. If the sodium montmorillonite-illite clay were going to disperse when subjected to freshwater, the exchange of calcium for sodium would only slightly lower this tendency. The chemical data were actually showing a solution to the problem rather than a cause of clogging. The fact that even low concentrations of calcium would exchange for sodium on the clay indicated that the clay would respond to chemical treatment.

LABORATORY DETERMINATION OF HYDRAULIC CONDUCTIVITY DETERIORATION

In order to substantiate the hypothesis that clay dispersion caused hydraulic conductivity deterioration in the aquifer, core samples of the injection sand taken during the drilling of OW-3 were sent to the hydrologic laboratory to determine if the aquifer was "water sensitive." Testing procedures were similar to the techniques described by Hewitt (1963). The cores were saturated with formation water for 24 hours prior to testing. Hydraulic conductivity was determined by running formation water through the core until the values

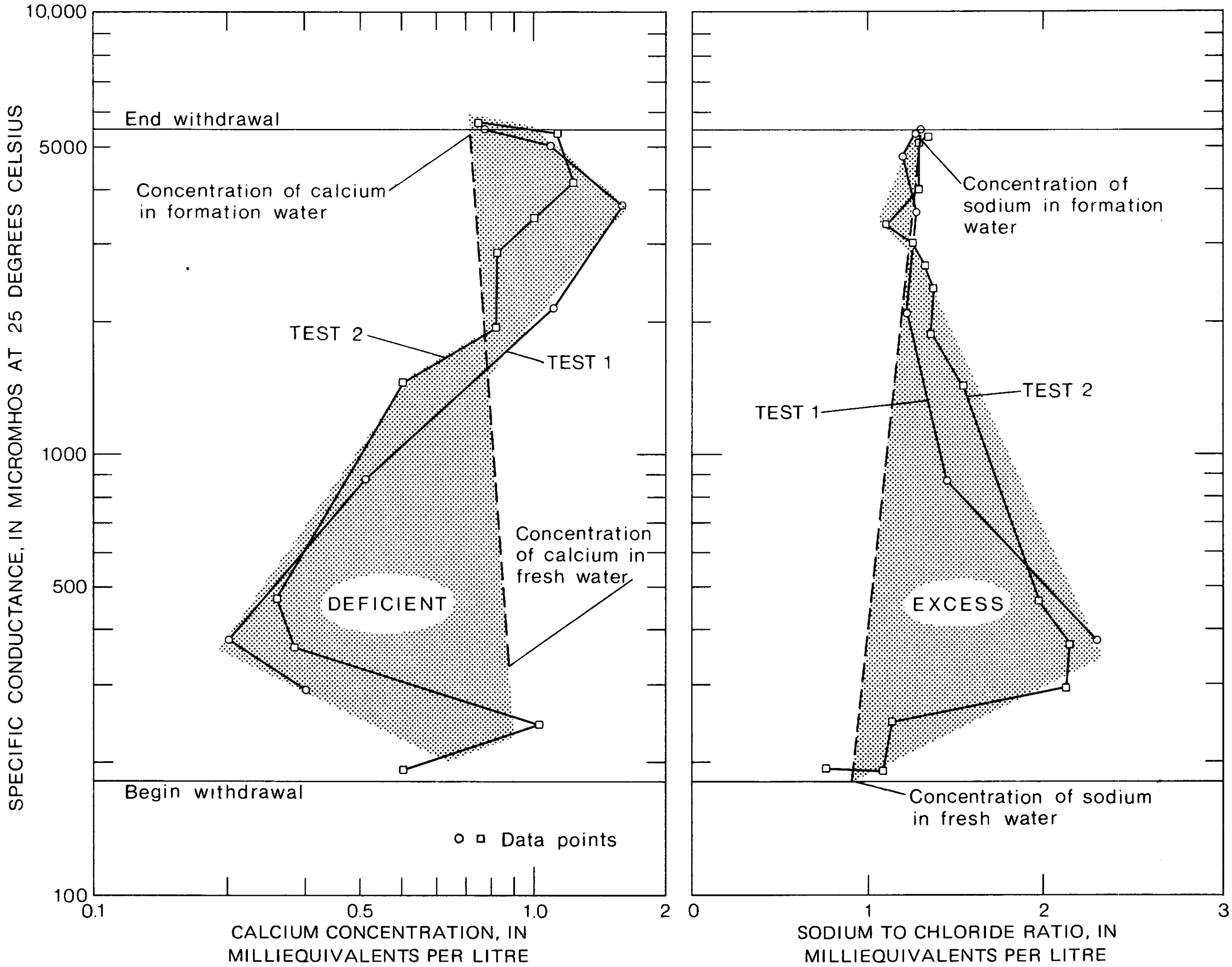


FIGURE 27.—Calcium concentration and sodium to chloride ratio versus specific conductance during the recovery of injected water, tests 1 and 2.

stabilized. City water was then introduced into the core, displacing the formation water. Hydraulic conductivity was measured until the value stabilized (table 10).

Laboratory results matched the field tests in that the hydraulic conductivity of the sand was irreversibly reduced. Reductions in hydraulic conductivity ranged from 50 percent to over 70 percent. The aquifer, on the basis of Hewitt's 1963 classification (water permeability-Klinkenberg (gas) permeability is less than 0.3), would be classified as strongly sensitive to freshwater.

Various chemicals were added to the city water to prepare a pre-flush prior to injection in an attempt to overcome the dispersion problem (table 10 and fig. 28). Sodium hydroxide and sodium carbonate were added to adjust the pH of the city water to values similar to, or greater than, that of the formation water. Deterioration of the hydraulic conductivity was not prevented by this treatment. Sodium hexametaphosphate, a compound used to clean wells that have had excessive invasion of drilling mud, was introduced into the core as a mixture in the city water. The compound did not prevent reduction in the hydraulic conductivity, and, because it acts as a dispersant, probably magnified the damage.

The fact that a turbid effluent resulted when either untreated or chemically treated city water was introduced into the core saturated with formation water indicates dispersion was occurring. When the city water was treated with calcium chloride, the double layer around the clay particles—and consequently the zeta potential—was reduced. No reduction in hydraulic conductivity occurred, and the effluent was clear, indicating dispersion and migartion of clay did not occur in any significant amount.

When a calcium chloride pre-flush was used (fig. 28, sample 73Va9), followed by untreated city water, a reduction in hydraulic conductivity of only 11 percent occurred. Reed (oral commun., 1973) has found that a 11-

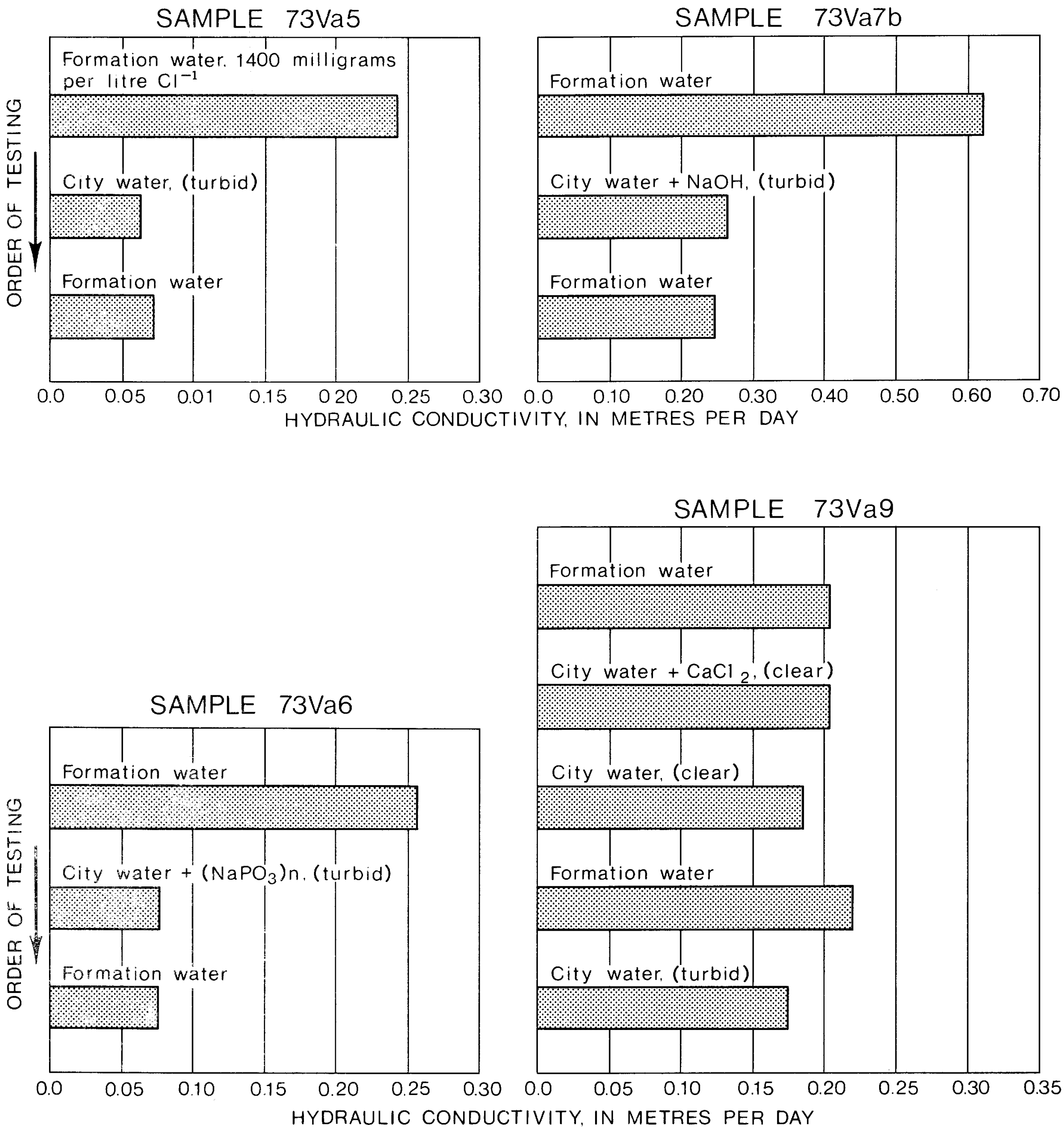


FIGURE 28.—Effects on the hydraulic conductivity caused by injecting city water containing various chemicals into a core saturated with formation water.

to 12-percent reduction in hydraulic conductivity occurs in wells treated with polymeric-hydroxy aluminum in water-flood projects and should be expected if either the calcium or aluminum treatment is used to stabilize clay. The core was resaturated with formation water, then injected with untreated city water. Clogging did occur, and the effluent was slightly turbid, indicating the calcium for sodium cation exchange is a reversible reaction. The reduction in hydraulic conductivity was not so severe as in previous tests, suggesting that the cation exchange may not be as complete when exchanging sodium for calcium at the concentrations used in this experiment. This is to be expected, as the calcium ion is held more tightly than the sodium ion.

TABLE 10.—*Effect of water chemistry on laboratory hydraulic conductivity for core samples from injection zone of observation well OW-3*

Laboratory sample number	Depth (ft)	Klinkenberg permeability (millidarcy)	(m/d)	Water type	Water modification	Input pH	Hydraulic conductivity (m/d)	Effluent condition
73Va2a	892–912	1050	8.7×10^{-1}	formation	none	8.5	4.2×10^{-1}	clear
2a		.....	.....	city	none	6.5	2.15×10^{-1}	turbid
2a		.....	.....	formation	none	8.5	2.42×10^{-1}	clear
2b	892–912	.....	.....	formation	none	8.3	4.98×10^{-1}	clear
2b		.....	.....	city	NaOH[1]	8.35	2.25×10^{-1}	turbid
2c	892–912	.....	.....	formation	none	8.3	1.34	clear
2c		.....	.....	city	Na_2CO_3[2]	10.2	4.52×10^{-1}	turbid
73Va5	955–975	1320	1.1	formation	none	7.5	2.43×10^{-1}	clear
5		.....	.....	city	none	6.5	6.49×10^{-2}	turbid
5		.....	.....	formation	none	7.5	7.2×10^{-2}	clear
73Va6	955–975	2150	1.8	formation	none	7.5	2.56×10^{-1}	clear
6		.....	.....	city	none	6.5	7.76×10^{-2}	turbid
6		.....	.....	city	$Na(PO_3)_n$[3]	.....	7.48×10^{-2}	turbid
6		.....	.....	formation	none	7.5	7.77×10^{-2}	clear
73Va7b	955–975	.....	.....	formation	none	7.0	6.2×10^{-1}	clear
7b		.....	.....	city	NaOH[4]	7.3	2.7×10^{-1}	turbid
7b		.....	.....	formation	none	7.0	2.5×10^{-1}	clear
73Va9	955–975	.....	.....	formation	none	.....	2.08×10^{-1}	clear
9		.....	.....	city	$CaCl_2$[5]	.....	2.08×10^{-1}	clear
9		.....	.....	city	none	.....	1.86×10^{-1}	clear
9		.....	.....	formation	none	.....	2.20×10^{-1}	clear
9		.....	.....	city	none	.....	1.74×10^{-1}	slightly turbid

[1]Enough added to bring pH equal to or greater than 8.3.
[2]40 mg/l added.
[3]100 mg/l added.
[4]Enough added to modify pH to between 7.0 and 8.0.
[5]1.375 grams per litre (0.14 percent solution) added.

INJECTION TEST 4

A fourth injection test was made to determine the effectiveness of chemically treating the clay to prevent dispersion under field conditions. Because the damage to the aquifer from clay dispersion during the first three tests severely reduced the capacity of the well to accept water, it was decided to use an inexpensive, nonpermanent, calcium chloride pre-flush treatment to stabilize the clay.

As the pre-flush moves away from the well screen, the calcium ions in the solution are exchanged onto the clay replacing the sodium ions. The pre-flush becomes a sodium chloride solution with time due to addition of sodium ions exchanged by the clay. Once the calcium ions in the pre-flush solution are reduced and reach the concentration of the formation water, the effectiveness of the pre-flush is negated, and dispersion, migration, and particle plugging occur in the aquifer. Thus, a decrease in injection rate and increase in injection head buildup will occur when the freshwater enters the untreated part of the aquifer away from the well.

It is neither practical nor necessary to treat the entire area that will come into contact with the injected water. In any problem of flow toward a well, the cross-sectional area of flow decreases sharply as the well is approached, and the greatest head losses occur close to the well. This can be shown by a simple application of Darcy's law, which states that as the cross-sectional area of flow decreases, the hydraulic gradient must increase, other factors remaining equal. In the present problem, this leads to the conclusion that if the area immediately around the well can be treated, most of the increased head losses, due to hydraulic conductivity deterioration, can be avoided. The exact distance from the well to which the treatment should extend is controversial; however, discussions with personnel from oil field service companies indicate that the preferred radius of treatment lies within the limits of 3 to 10 ft (0.9 to 3 m) from the borehole.

Injection test 4 was begun Nov. 24, 1972. A pre-flush of 3,000 gal (11 m³) of 0.2*N* calcium chloride was injected in front of the city water. Based on current-meter data, this volume would theoretically treat the aquifer to a radius of 8 ft (2 m) in the most permeable zones.

The injection rate stabilized at 185 gal/min (12 l/s) after 10 minutes and was maintained at that rate for 115 minutes. The hydraulic gradient declined throughout this time indicating that the treatment was working effectively. After 115 minutes, the injection rate began to decline slowly, and the injection head pressure began to increase slowly. At this point, over 20,000 gal (76 m³) had been injected, and the freshwater was beyond the area of treatment.

It was suspected that redevelopment pumping would increase the specific capacity of the well, but redevelopment pumping could not be attempted until a sufficient quantity of freshwater was injected to ensure that formation water was not brought back into the vicinity of the wellbore. Because the calcium for sodium base exchange is reversible, if formation water were brought into contact with the "desensitized clay," it would return them to a water-sensitive condition.

Continuous injection of 398,000 gal (1,510 m³) was made over a 2,580-min (1.79-day) period before any redevelopment pumping was attempted. Water was then injected for periods of 11,380 min (7.9 days), 10,025 min (6.96 days), 2,495 min (1.73 days), 2,695 min (1.87 days), and 20,450 min (14.2 days) between redevelopment pumpings. After the 20,450-min injection phase, redevelopment pumping was done on a daily basis. Thirty-nine injection phases were used over a period of 95 days in order to inject a total of 20,146,100 gal (76,250 m³) of freshwater into the brackish-water aquifer.

INJECTION SPECIFIC CAPACITY

Figure 29 shows the injection specific capacity of IW-2 during the early part of test 4 as compared to the specific capacity measured during pre-injection and injection tests 1, 2, and 3. In the first 1,000 min, the decrease in specific capacity was 51 percent in test 2, 75 percent in test 3, and only 32 percent in the initial phase of test 4. A 40-percent decrease in specific capacity occurred during the initial 260 minutes of test 1. The expected decrease in specific capacity with time, based on pre-injection aquifer test data, is about 15 percent.

After the initial injection phase of test 4, the decrease in specific capacity during the first 1,000 min of injection for each new injection period following redevelopment ranged from 3 to 20 percent. The variation in percentage of decrease reflects the effectiveness of redevelopment pumping. A decrease of 11 to 12 percent per initial 1,000 min of injection is an average value for test 4. This value agrees with the decrease Reed (oral commun., 1973) found to occur in treated water-flood wells and with the decrease in laboratory hydraulic conductivity when freshwater was injected into core treated with a calcium chloride pre-flush (table 10).

Figure 30 shows that each redevelopment pumping period increased the specific capacity of the injection well. After discharging the water standing in the well casing (about 3,000 gal or 11 m³), the water first pumped from the

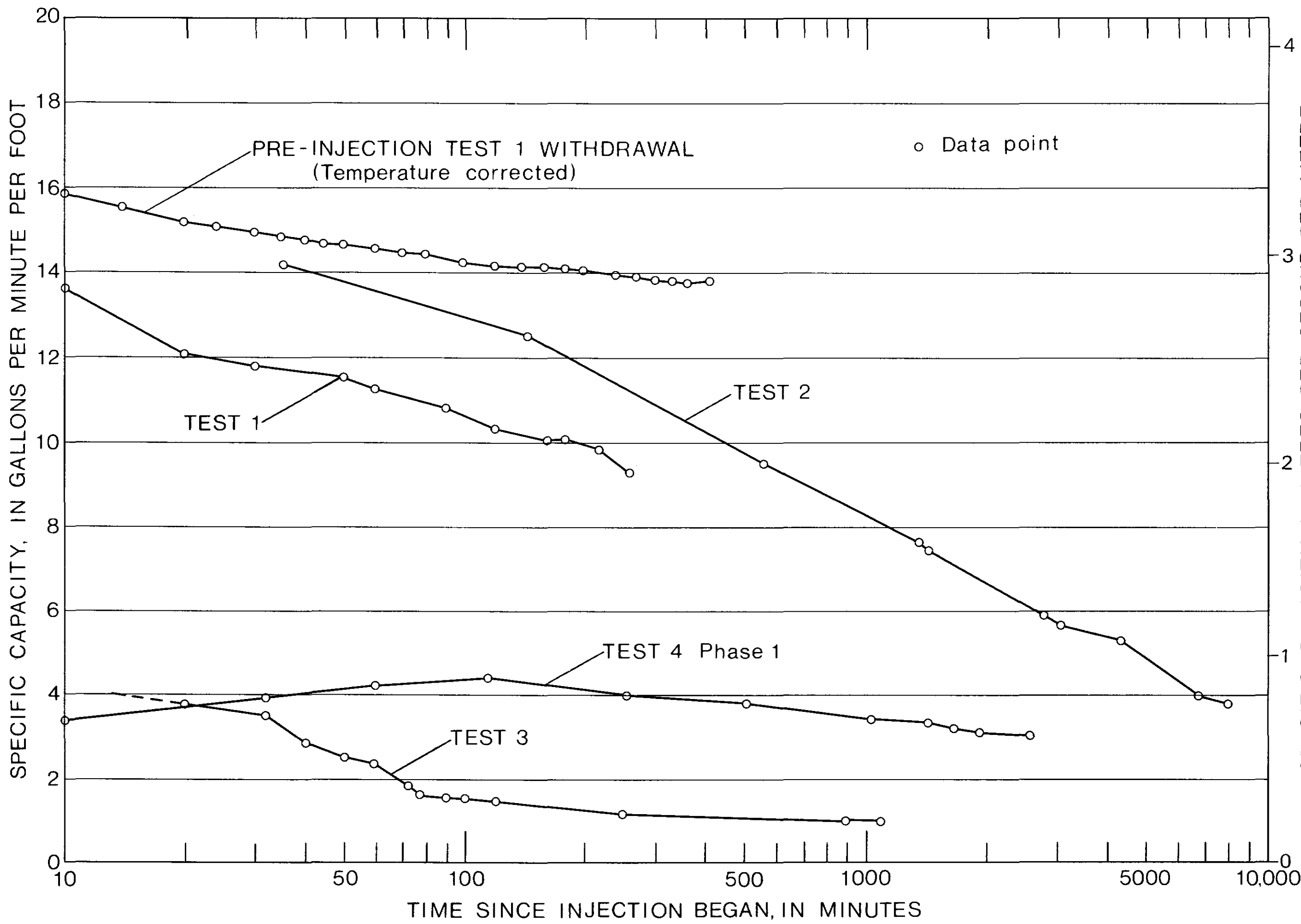


FIGURE 29.—Variations in specific capacity of injection well IW-2 during injection tests.

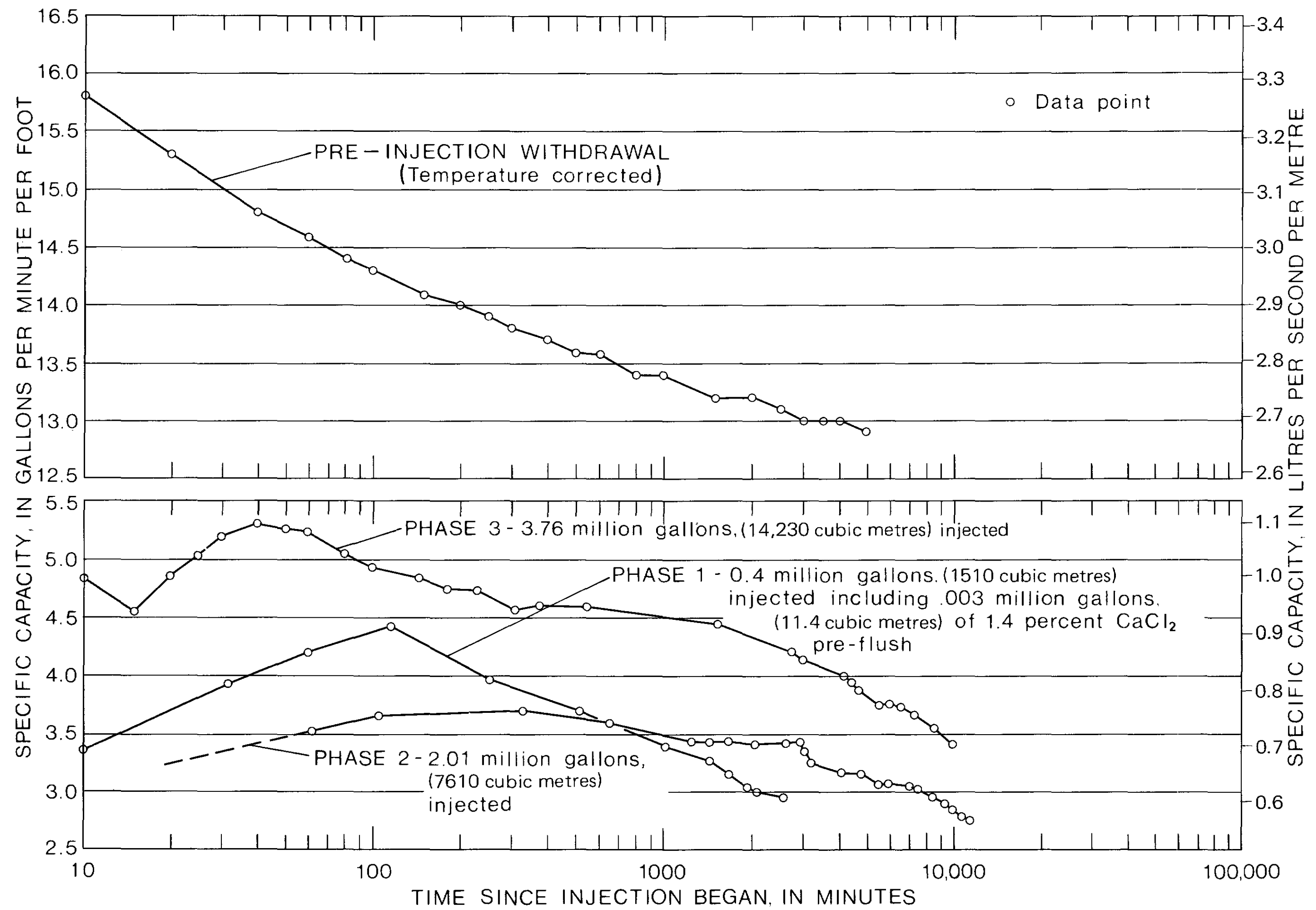


FIGURE 30.—Specific capacity of injection well IW-2 prior to any injection of freshwater and variation of specific capacity during test 4.

aquifer contained sand, clay, and mica in excess of 360 mg/l. The water was heavily laden with sediment for 5 to 6 minutes during the first redevelopment pumping, but the large sediment concentration had decreased until it existed for less than a 1-minute duration after the fourth redevelopment pumping. The sediment coming from the well contained microfossils and glauconite particles that are foreign to the aquifer. This material probably represented drilling-mud invasion into the gravel pack and formation during construction of the well. The clay particles coming from the well were flocculated and probably represented material lossened during treatment by the calcium chloride.

Sediment was noticed in the redevelopment discharge from IW-2 following injection test 2. Development pumping, by alternately surging and injecting water, produced large concentrations of sand prior to and after test 3. The sediment recovered during that development attempt was identical to that recovered during test 4, with the exception that the clay was in a dispersed state prior to test 4.

The specific capacity of IW-2 improved with redevelopment pumping, and the amount of sediment discharged decreased during the redevelopment pumping of injection test 4. It was believed that the well yield could be further improved if sediment movement could be prevented completely. Coppel (oral commun., 1973) stated that treatment to desensitize water-sensitive aquifers has reduced or prevented sand production in wells that had a history of sand production. Reed (oral commun., 1973) suggested that the 0.2*N* solution of calcium chloride pre-flush was not the most efficient concentration to stabilize the clay and recommended the injection of another pre-flush using a 0.4*N* solution. After 4.04 Mgal (15,290 m^3) had been injected, 3,000 gal (11 m^3) of a 0.4*N* calcium chloride solution was injected in front of untreated city water.

Figure 31 shows the injection specific capacity for the calcium chloride water, and the specific capacity recorded after two subsequent redevelopment periods. The specific capacity during injection phase 5 showed a marked improvement for about 60 minutes following the treatment with the calcium chloride solution but then declined at a greater rate (27 percent between 60 and 1,000 min) than the 11- to 12-percent average decrease. The specific capacity for the injection phases 6 and 7 ranged from 3.3 to 5.8 $gal/min^{-1}ft^{-1}$ (0.68 to 1.2 $ls^{-1}m^{-1}$) and decreased at a rate similar to that of phase 4 (fig. 30). Thus, the aquifer characteristics did improve significantly with the additional treatment but clogged again sometime after 120 min of injection. The sand flow during the redevelopment periods diminished but did not completely stop.

Figures 30 and 31 show that an optimum specific capacity value can be maintained if the injection period is limited to about 1,440 min (1 day). In IW–2, considering the altered condition of the aquifer and the sediment discharge, the most efficient method was to inject for about 1,440 min, withdraw for 30 min to clear the screen of sediment, wait 1 hour to allow the water level to approach static conditions, and then begin the next injection.

Figure 32 illustrates that the injection specific capacity did not vary significantly from the time 9.05 Mgal (34,250 m^3) had been injected through the time 15.87 Mgal (60,070 m^3) had been injected. After injecting 16.35 Mgal (61,890 m^3), the specific capacity deteriorated and redevelopment pumping could not restore it.

CURRENT-METER TRAVERSES

Figure 33 shows the pre-injection test 4 flow pattern and the flow patterns observed during the injection phase of test 4. The injection flow pattern shows that essentially no water is entering the aquifer deeper than 930 ft (283 m) below sea level. This interval, based on the pre-injection test-4 traverse, should have been taking about 45 percent of the total flow. The flow pattern suggests particulate clogging in the screen and gravel pack rather than the uniform reduction in flow percentages that occurred when clay dispersion affected the hydraulic conductivity of the aquifer as shown in tests 1 and 2. The withdrawal current-meter traverses (fig. 34) show that the flow pattern returns to the pre-injection test 4 pattern, indicating that the sediment lodged in the screen was removed during the initial surge of withdrawal pumping.

Within the zones taking water, little clogging occurred during the injection of the first 15 Mgal (56,800 m^3) of freshwater (fig. 33). The current-meter traverses show that in the zone taking the highest percentage of the water at the start of the test (903 to 915 ft or 275 to 279 m below sea level) only 3 ft (0.9 m) at 912 to 915 ft (278 to 279 m) below sea level had clogged after nearly 63 days of injecting. During the first 63 days of injecting, the specific capacity of the well had remained rather uniform. When the specific capacity of IW–2 began declining rapidly (after 16 Mgal or 60,600 m^3 had been injected), it was suspected that

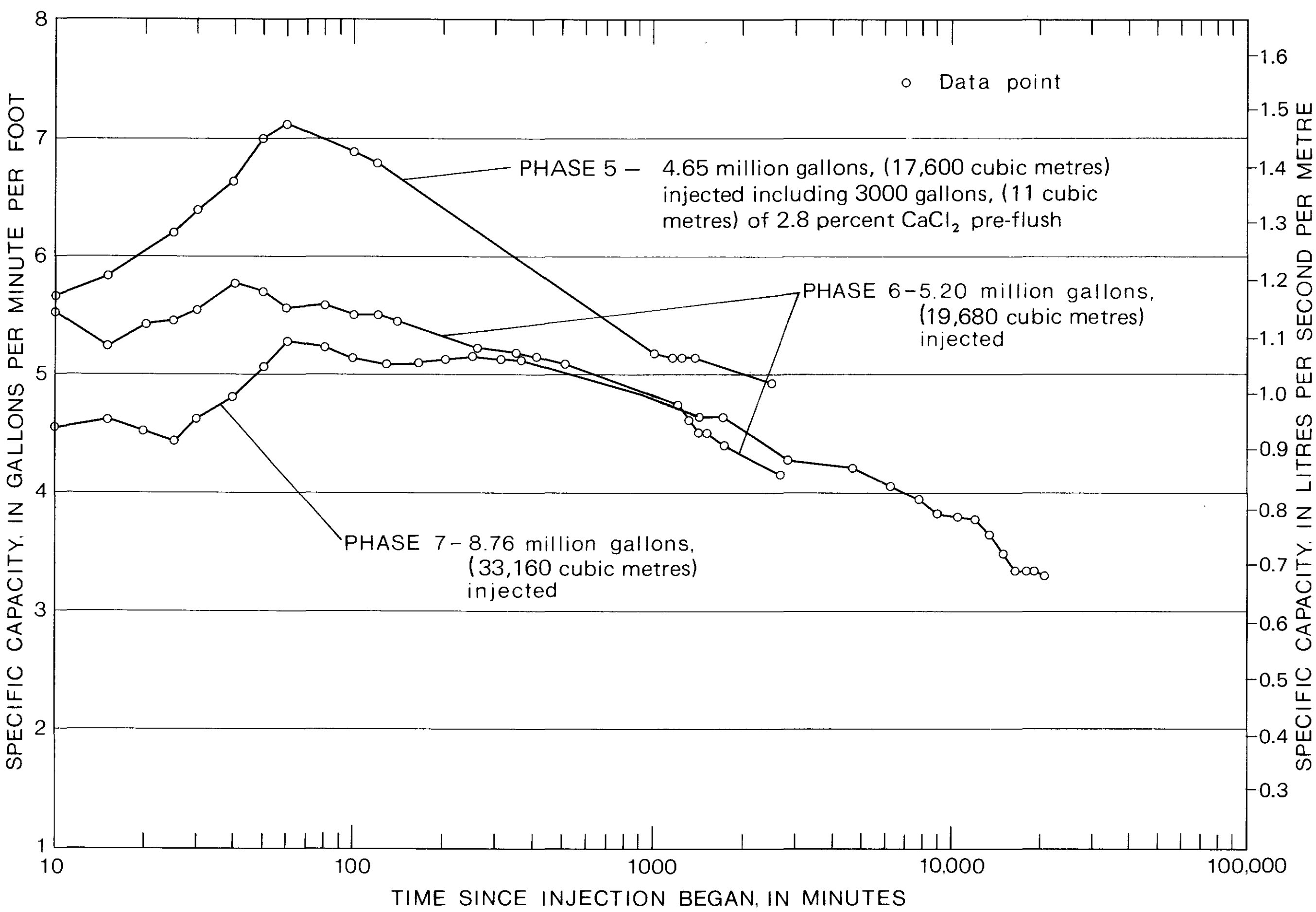
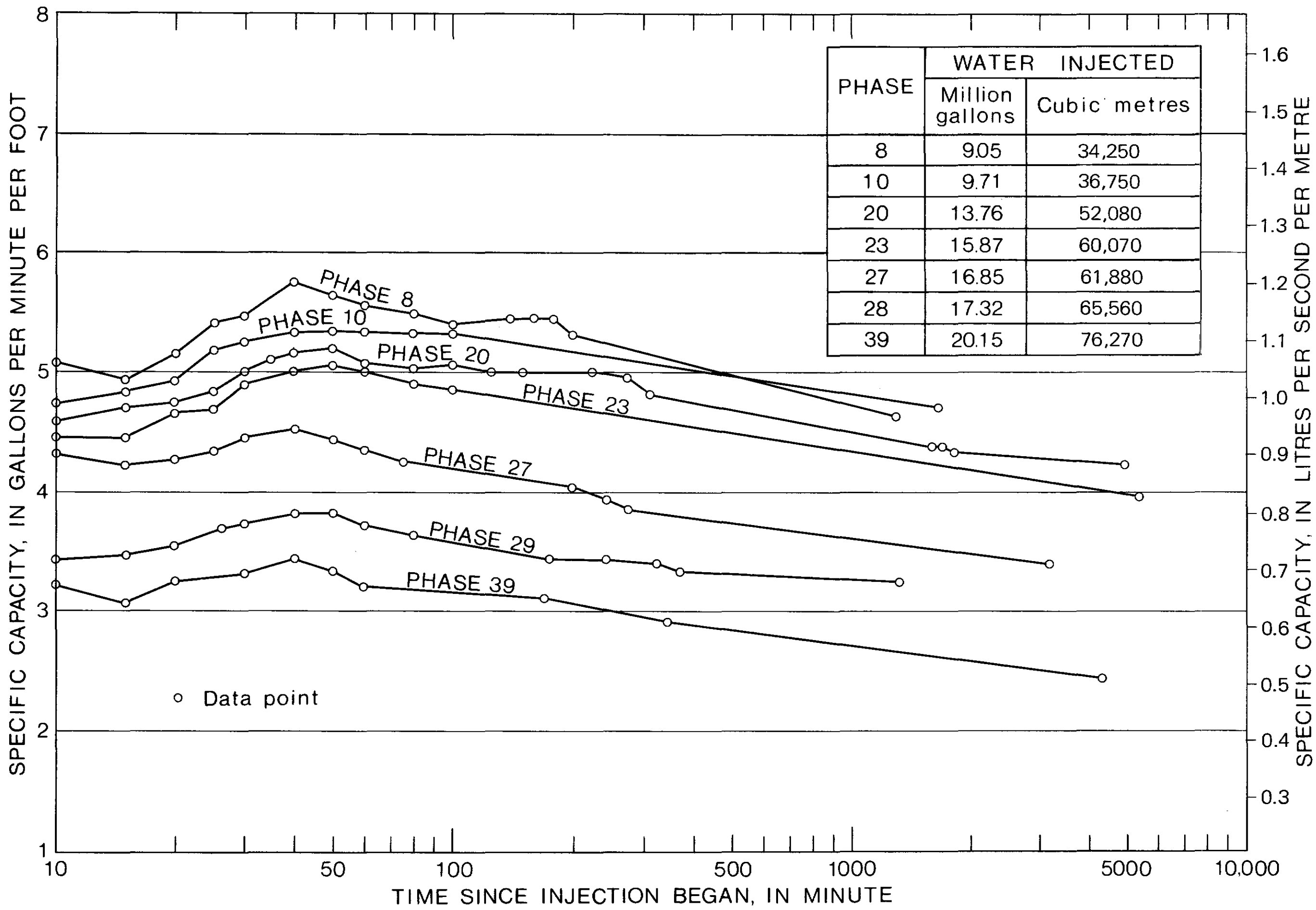


FIGURE 31.—Variation of specific capacity in injection well IW–2 for injection phases 5, 6, and 7, test 4.



PHASE	WATER INJECTED	
	Million gallons	Cubic metres
8	9.05	34,250
10	9.71	36,750
20	13.76	52,080
23	15.87	60,070
27	16.85	61,880
28	17.32	65,560
39	20.15	76,270

FIGURE 32.—Variation of specific capacity in injection well IW-2 for injection phases, test 4.

clogging was occurring within the aquifer above the depth of 930 ft (283 m) below sea level. The current meter was inoperative at this time, however, and traverses could not be made to confirm the suspicion.

Prior to treatment of the aquifer with the calcium chloride, the zone from 904 to 922 ft (276 to 281 m) below sea level accepted a maximum of 50 percent of the water injected. After treatment with a calcium chloride solution, the zone took between 80 and 90 percent of the water injected. This fact suggests that the treatment may have operated preferentially in this zone. It was the most permeable zone and would accept most of the calcium chloride solution and show the greatest improvement in hydraulic conductivity. The preferential treatment of this zone may have taken so much of tahe calcium chloride solution that only a token amount reached the aquifer below 922 ft (281 m). Therefore, when the pre-flush was followed by freshwater, dispersion and clogging by sand and clay particles occurred below 922 ft (281 m).

CAUSE OF CLOGGING OF IW-2 DURING INJECTION PHASE OF TEST 4

The quantity of sediment produced during the redevelopment phases up through 16.35 Mgal (61,880 m^3) injected in test 4 usually diminished after about 1 or 2 minutes of redevelopment pumping. After injecting 16.35 Mgal (61,880 m^3) of freshwater, the heavy discharge of sediment obtained during the daily redevelopment lasted for 8 to 10 minutes. Not only had the quantity of sediment increased, but the character of the sediment also changed. It consisted predominately of clay granules with some colloidal clay and silt to fine-grained particles of quartz and mica. The granules consist of flocculated clay and silt. The colloidal clay remained in suspension for several hours in undisturbed water but not for days, as it had before treatment.

A possible cause for the large amount of sediment discharge and the subsequent decrease in specific capacity may have been due to disturbance of the gravel pack, so that its effectiveness as a filter was decreased. During the redevelopment cycle, a combination of injection and withdrawal pumping was employed; this practice tends to agitate the gravel pack of the well. It was after this vigorous redevelopment pumping that the sediment discharge during withdrawal became noticeably larger and lasted up to 15 minutes before diminishing.

The appearance of some dispersed clay and the overall

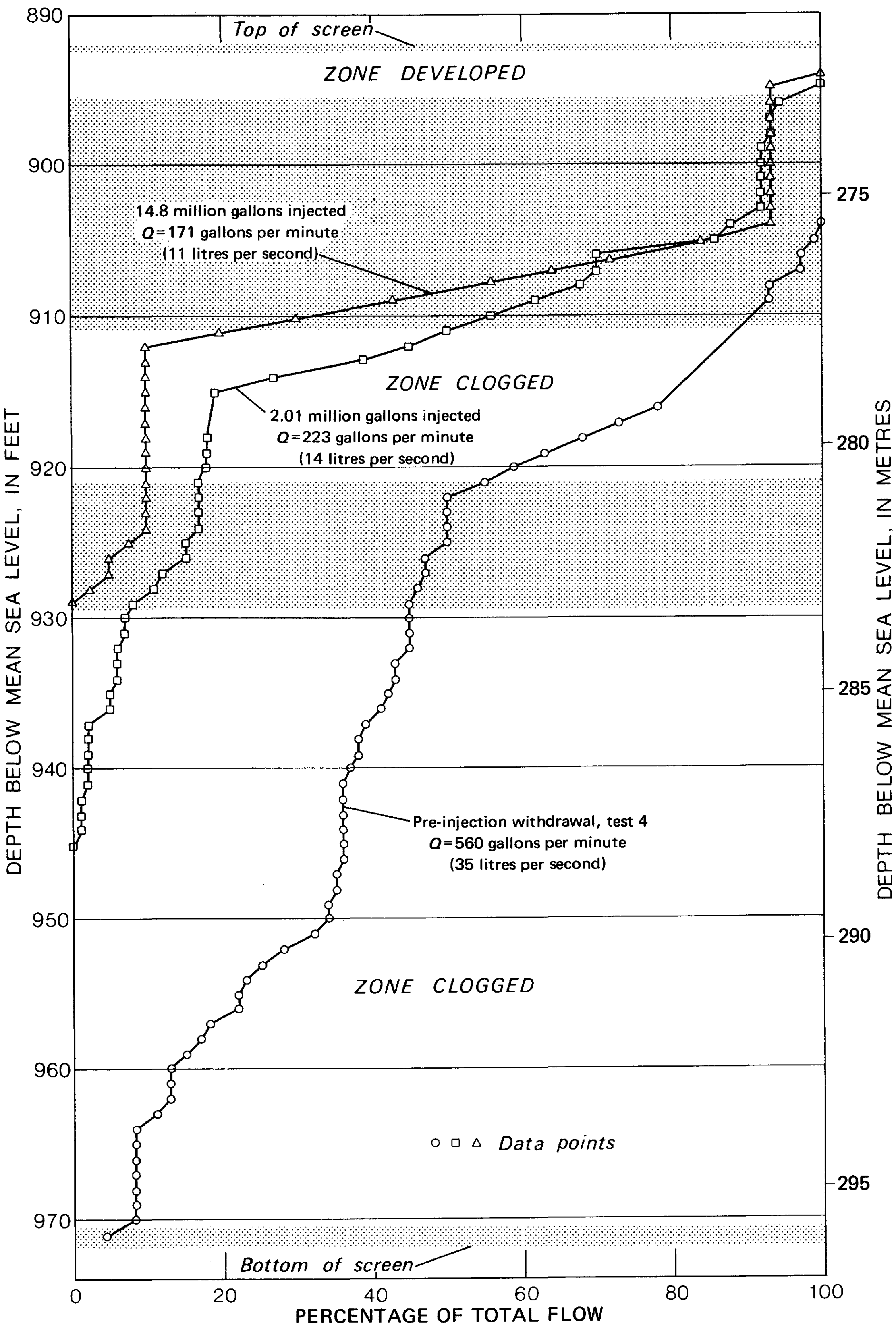


FIGURE 33.—Current-meter traverses in injection well IW-2 of pre-injection and injection flow, test 4.

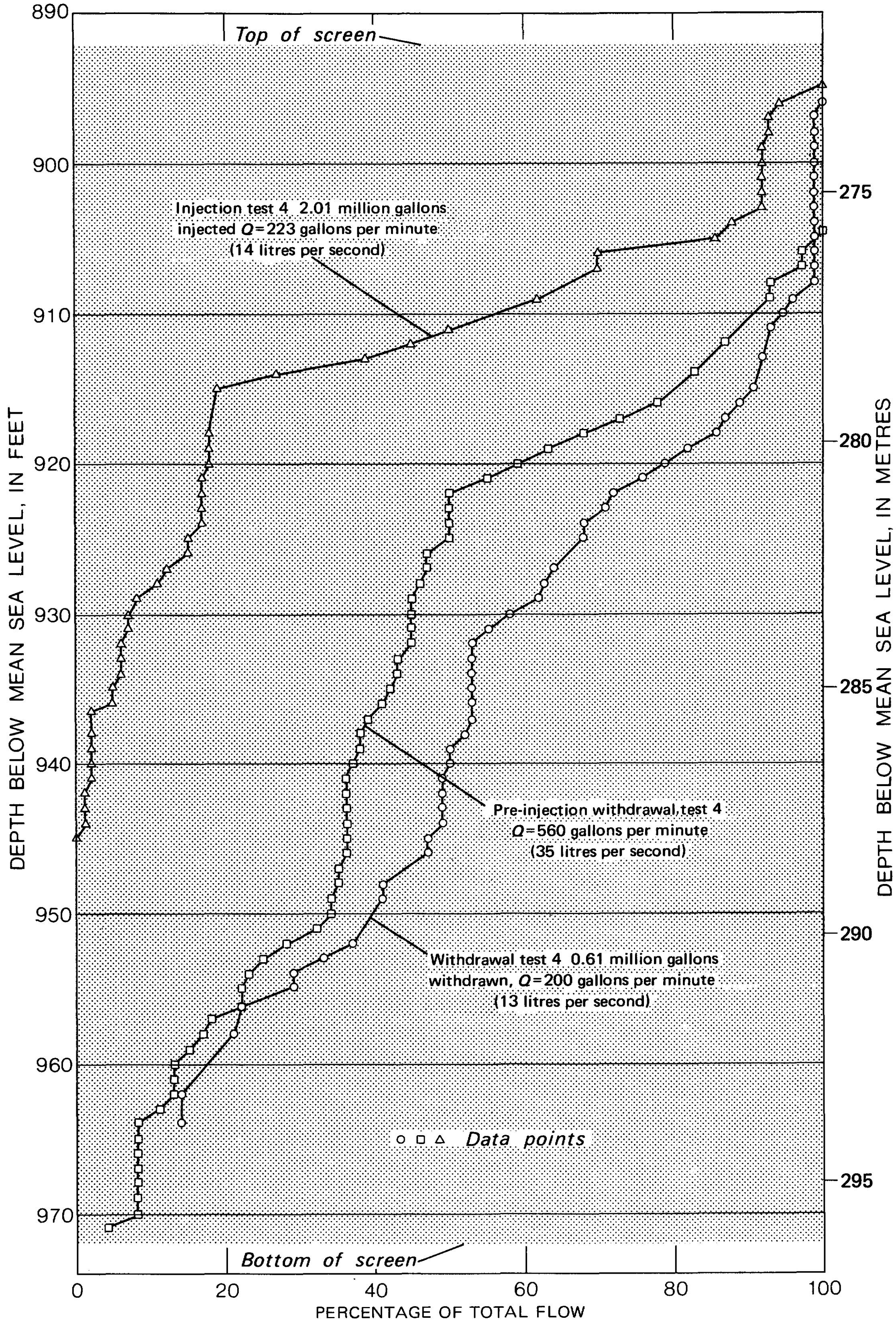


FIGURE 34.—Current-meter traverses in injection well IW-2 of pre-injection, injection, and withdrawal flow, test 4.

decrease in size of the sediment indicated that the sediment may have been coming from the aquifer below 922 ft (281 m) below sea level, which did not receive effective calcium chloride treatment. During redevelopment pumping, the higher pumping rates produced appreciable water from the lower part of the aquifer with enough velocity to move clay and silt into the borehole. As pumping continued and the rate fell off, the velocity of the water coming from the lower section was not sufficient to move the sediment into the borehole.

The sand trap below the screen may have been the source of most of the sediment that caused particulate clogging. As injection began, after each phase of redevelopment pumping in test 4, the surge of water into the wellbore and screen could agitate the material into suspension, so that injection of sand and clay particles into the screen and gravel pack could take place. During redevelopment, the current meter indicated water movement in the bottom 40 ft (12 m) of the well, but during injection it indicated no water movement even though the pumping rates were comparable.

The phenomenon may occur because the screen is designed for withdrawal pumping. The openings of the screen are V-shaped with the open end of the V facing inward. During normal withdrawal pumping, particles passing through the smallest opening enter the well and are removed, provided the well is pumping at sufficient rates to keep the sand in suspension. However, if the sediment clogging the well is coming from agitation of an internal source (such as the fill-up pipe) while injection is occurring, the sand would lodge in the screen and block the flow of water. Upon withdrawal pumping, the shape of the openings would allow easy removal of the material and open the screen to flow from the aquifer.

Figure 35 shows that below 950 ft (290 m) below sea level, the screen in IW–2 contributed a larger percentage of the total flow as withdrawal pumping progressed, indicating that development occurred within the zone. The flow from 946 to 960 ft (288 to 293 m) increased from 23 percent to 36 percent of the total flow after 26.3 Mgal (99,550 m^3) had been withdrawn. At the same time, the percentage of total discharge from 910 to 922 ft (277 to 281 m) below sea level decreased from 41 to 13 percent. Both the chemical and hydraulic data suggest that the clay in the gravel pack in the 910- to 922-ft (277- to 281-m) zone was exposed to the brackish water, which resulted in repacking, which, in turn, reduced the flow from that zone.

CHEMICAL EFFECTS OBSERVED DURING WITHDRAWAL PHASE OF TEST 4

Chemically, the following sequence of events were predicted during the withdrawal phase of test 4: (1) The specific conductance of the first water withdrawn would be about equal to the input value; (2) the specific conductance would remain below 1,000 micromhos until approximately 17 Mgal (64,300 m^3) was withdrawn; and (3) the calcium concentration in the repumped water would remain at 15 to 17 mg/l, assuming that most of the calcium in the calcium chloride solution was exchanged by the clay. There would be some increase in the concentration of sodium at the outer edges of the freshwater zone, corresponding to periods in which the calcium chloride was injected (calcium for sodium exchange). The calcium concentration in the repumped water would not increase above 17 mg/l until the concentration of sodium in the mixed freshwater and formation water rose to between 600 and 700 mg/l. At that point, a reverse exchange would occur, which would indicate the return to a high percentage mixture of native water, including some exchanged sodium.

During this later period of pumping, the calcium concentration would remain relatively high until most of the exchanged calcium had been replaced by sodium from the formation water. These events were predicted on the basis of data observed during withdrawal phases of tests 1 and 2.

The authors were aware that most of the water was injected selectively in the interval 910 to 930 ft (277 to 283 m) below sea level. It was expected that the stabilization of the clay in that zone, combined with the clogging in the bottom of the aquifer, would cause the withdrawal flow pattern to be the same as the injection flow pattern. However, this did not occur during test 4 withdrawal, and the flow pattern reverted to the pre-injection flow pattern (fig. 35), causing many of the predicted chemical reactions to be masked.

After 8 Mgal (30,300 m^3) of water had been withdrawn, the zone that had taken 80 percent of the water during injection (904 to 915 ft (276 to 279 m) below sea level) was yielding less than 10 percent (fig. 36). Further, it can be seen that zones that took little or no freshwater began to develop and were yielding formation water. As pumping continued and after 17 Mgal (64,300 m^3) of water had been withdrawn, more than 50 percent of the water coming out of the well was formation water (fig. 37). Based on the chloride concentration, less than 20 percent of the water recovered was potable (U.S. Department of Health, Education, and Welfare, 1962) (fig. 38).

The net result of this differential yield between injected and withdrawn freshwater was that predicted chemical observations were obscured by the preponderance of formation water. The specific conductance was above 1,000 micromhos after only 4.2 Mgal (15,900 m^3) was withdrawn instead of 17 Mgal (64,300 m^3), as was predicted. The calcium content did show some deficiency in the first water withdrawn, indicating some base exchange still occurred in test 4. The deficiency of calcium in test 4 was minor compared to the calcium deficiency recorded in the first three tests, and was further evidence that treatment of

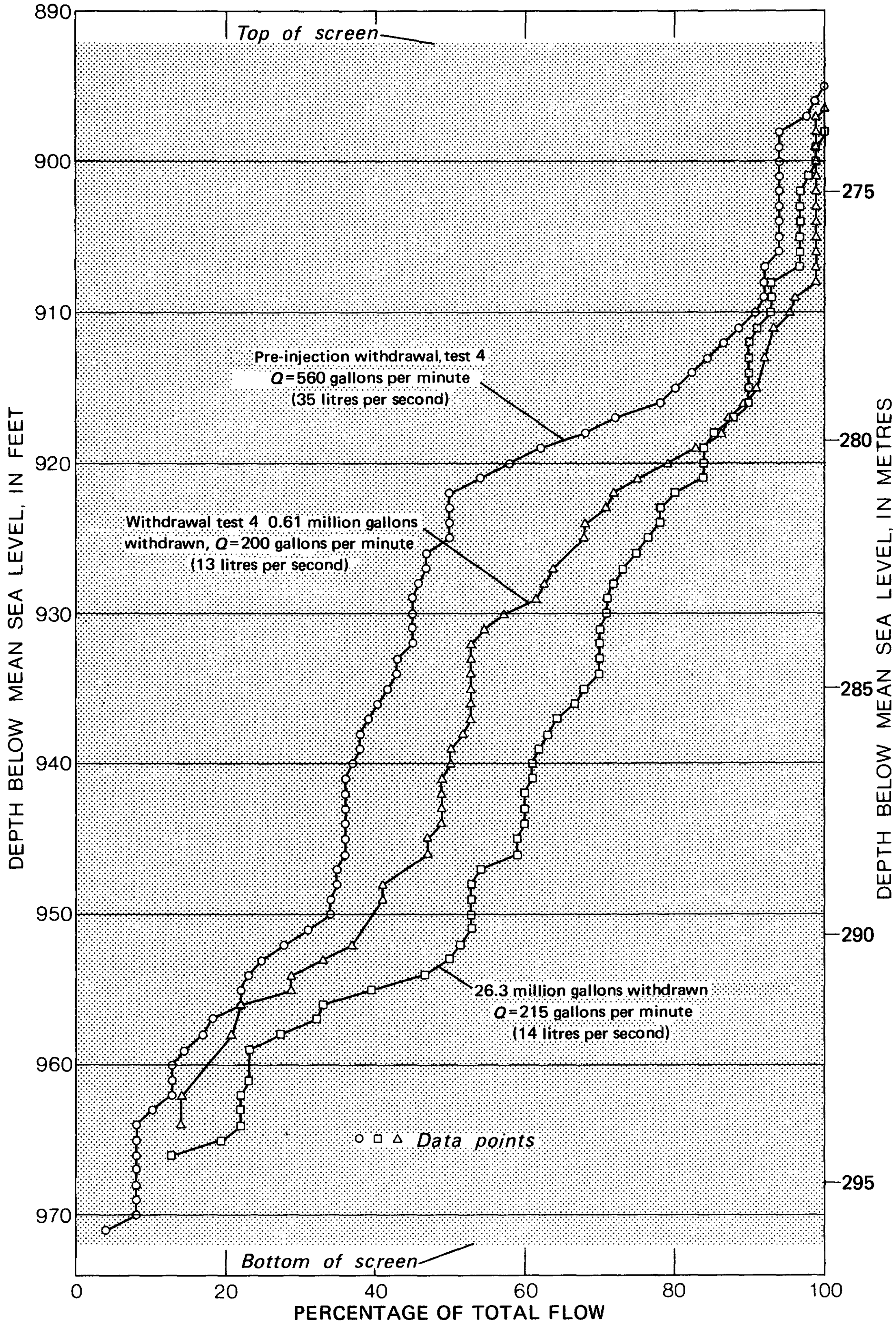
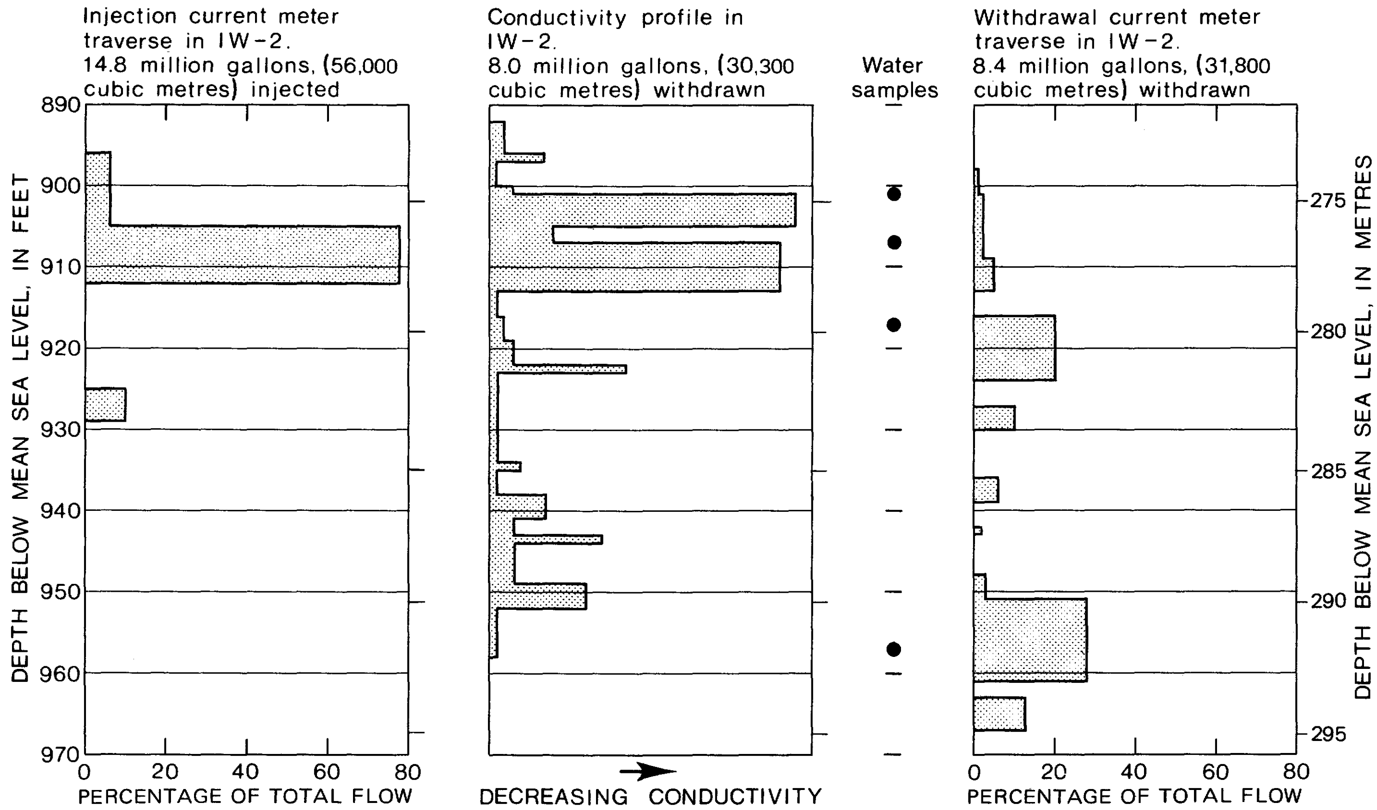


FIGURE 35.—Current-meter traverses in injection well IW-2 of withdrawal flow, test 4.



WATER SAMPLES COLLECTED BY THIEF SAMPLER, 5-30-73			
Depth below mean sea level		Chloride (mg/l)	Specific conductance (Micromhos)
Feet	Metres		
901	275	670	2900
907	276	700	3100
917	280	880	3800
957	292	1200	4800

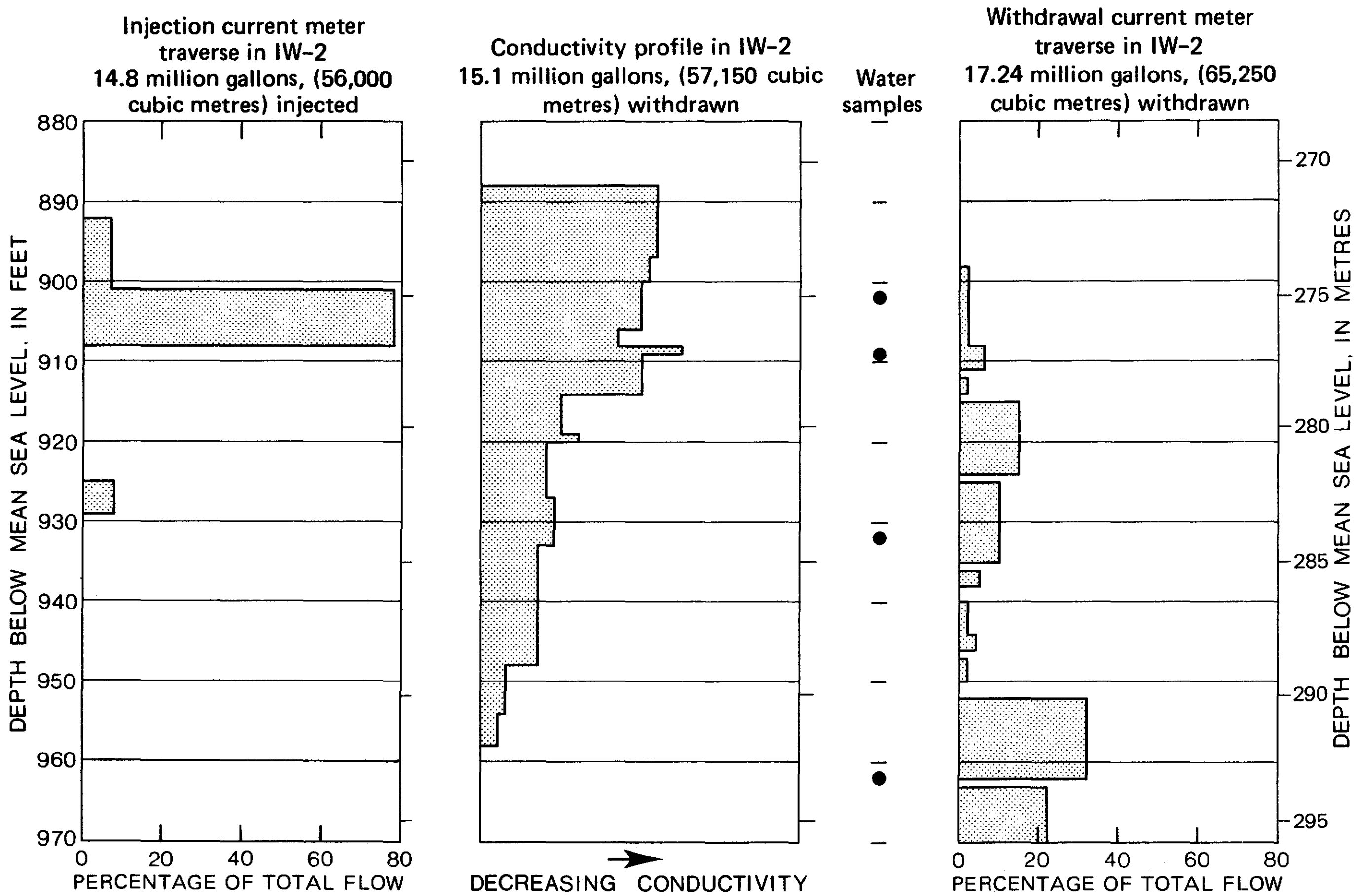
FIGURE 36.—Changes in injection and withdrawal flow and conductivity profile in injection well IW-2 after 8 Mgal (30,300 m^3) withdrawn, test 4.

the lower 40 ft (12 m) of the aquifer by the calcium chloride pre-flush was not complete.

The variation in concentration of calcium and sodium indicated a reversible reaction was occurring in test 4. As shown in tests 1 and 2, this reaction normally begins to take place at low conductivity values. The immediate influx of formation water from the lower 40 ft (12 m) of the aquifer raised the conductivity and dissolved-solids concentration of the first water withdrawn to such an extent that a clear definition of the reactions was not possible.

In all the previous tests, the temperature functioned as a straight-line dilution and apparently continued to do so in test 4. The pH data, however, did show the effects of stabilization of the clay. In tests 1, 2, and 3, water of pH 5.4 to 6.0 was injected into the formation, displacing water of 7.9 pH. When the water was withdrawn, the pH was between 9 and 10 until the percentage of formation water in the mixture became greater than the percentage of freshwater. It was suspected that this condition was a result of cation exchange whereby one equivalent of sodium carbonate in the freshwater would produce a higher pH than one equivalent of calcium bicarbonate. As the saltwater was drawn back into the well and the base exchange reversed, the pH returned to the original formation value. When the clay was stabilized in test 4 and cation exchange was confined to the partly treated lower part of the aquifer, the pH of the first water withdrawn did not rise above 8.0.

Dissolved oxygen, which ranged between 8 and 11 mg/l during all tests, was lost during each test. The immediate assumption was that the dissolved oxygen was involved in reactions with iron or manganese or some organic material. However, there was less than 0.1 mg/l iron or manganese in either the injected freshwater or formation water. The organic content, in terms of chemical-oxygen demand, was exceedingly low (less than 2 mg/l). The loss



WATER SAMPLES COLLECTED BY THIEF SAMPLER 5-30-73			
Depth below mean sea level		Chloride (mg/l)	Specific conductance (Micromhos)
Feet	Metres		
902	275	880	3800
909	277	880	3700
932	284	1200	4900
962	293	1400	5800

FIGURE 37.—Changes in injection and withdrawal flow and conductivity profile in injection well IW-2 after 15.1 Mgal (57,150 m³) withdrawn, test 4.

of dissolved oxygen is an immediate reaction during injection but has little effect on the potability of the water. Although plugging by gas bubbles is a possibility, saturation and head data suggest that the hydraulic properties of the aquifer were not noticeably affected by the loss of dissolved oxygen.

ANALYSIS OF PROJECT

The Norfolk injection project has demonstrated that the sand aquifers containing saline water in the Norfolk area, and quite likely throughout the Coastal Plain, are water sensitive and must be treated as such if they are to be recharged with freshwater. Moreover, if physical clogging of the screen of the injection well can be prevented during injection of freshwater, the percentage of recoverable potable water is sufficient to make the proposal of underground storage and retrieval of freshwater from a brackish aquifer feasible.

During injection tests 1 and 2, 65 percent of the water recovered was within Public Health Service standards, and as much as 85 percent of the mixed water recovered could be used if necessary. During these two tests, the clogging of the aquifer, due to clay dispersion, caused a uniform reduction in aquifer hydraulic conductivity.

The first three injection tests were conducted prior to identifying the water-sensitive nature of the aquifer. Consequently, deterioration of aquifer properties as a result of injecting freshwater was irreversible, and original condi-

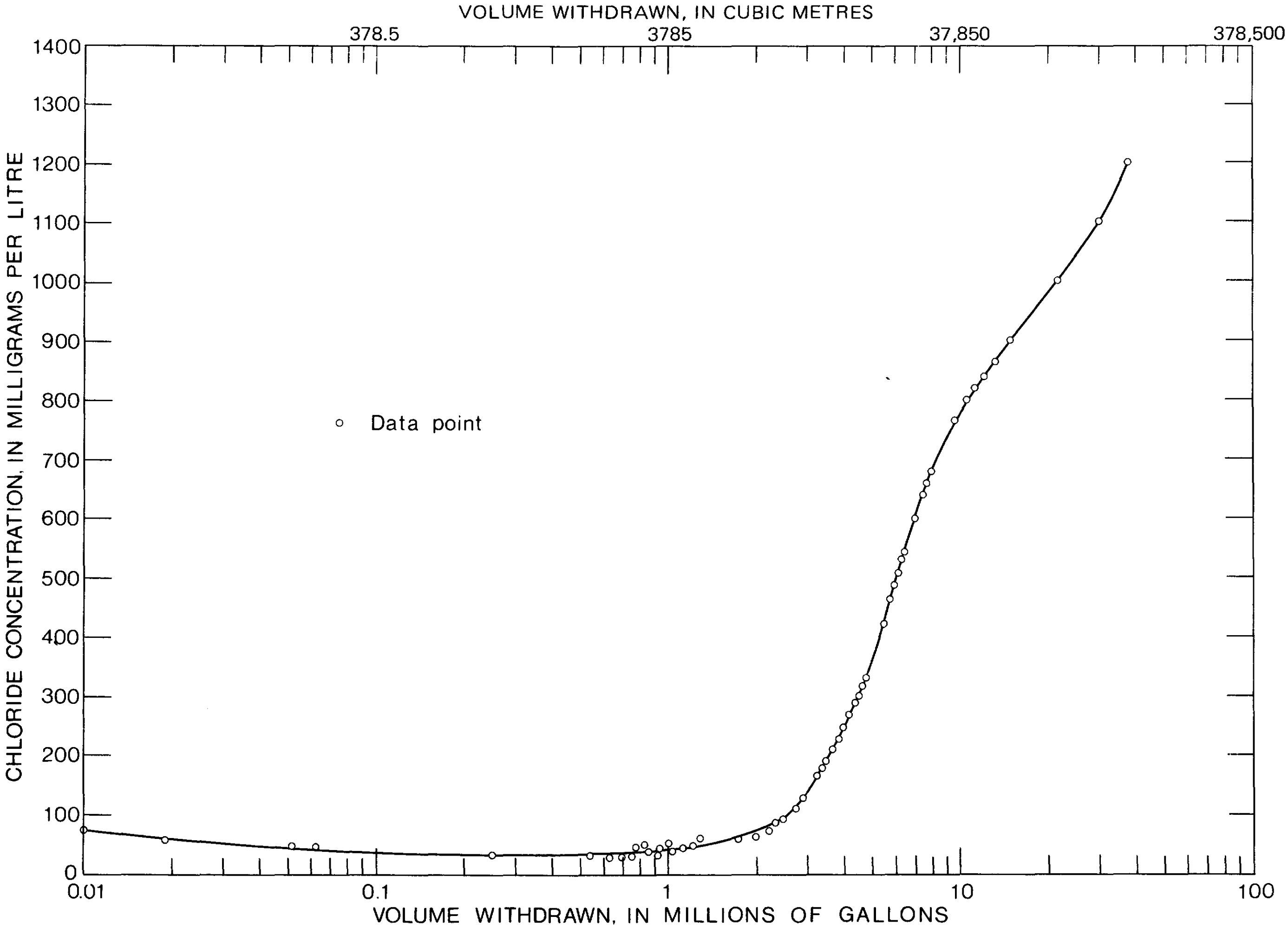


FIGURE 38.—Changes in chloride concentration with volume of water withdrawn, test 4.

tions could not be restored. Treatment of the clay to prevent further deterioration of the aquifer hydraulic properties was possible, as evidenced by the injection phase of test 4. However, the aquifer deterioration had progressed to the point that physical clogging of the screen and the gravel pack was the dominant factor in the injection process.

Current-meter traverses made during injection and withdrawal in tests 1 and 2 showed that zones taking water during injection gave up water during withdrawal in approximately the same percentage of the total discharge. That is, a zone that took 10 percent of the water injected also yielded 10 percent of the water during withdrawal. This demonstrates that the injection front was predictable, provided that clogging did not occur and cause variations in flow patterns between injection and withdrawal.

The importance of preventing clogging can be seen from the low recovery percentages of potable water during tests 3 and 4. Because of the water sensitivity factor, the deterioration of the aquifer had progressed to the extent that clogging by sand and clay particles became the dominant factor in the injection process. Current-meter traverses showed that the injection flow patterns had changed drastically from those of tests 1 and 2. Zones that had taken water during injection tests 1 and 2 clogged completely during tests 3 and 4, resulting in localized rather than uniform injection of freshwater.

Current-meter traverses made during withdrawal pumping are consistent and similar to those made prior to injection of any freshwater. Zones that clog during injection become productive during withdrawal and produce nearly the same percentage of the total discharge from the well as was produced during pre-injection conditions. As a result, when withdrawal pumping commenced in tests 3 and 4, flow came not only from the zones that took freshwater but from the previously clogged zones that contained formation water. Consequently, only 20 percent of the water recovered in test 4 was potable.

Sand production during withdrawal and development pumping in IW-2 after test 2 was coincident with the particulate clogging on the screen and in the gravel pack.

It is unclear, at this time, whether clay dispersion and repacking within the aquifer allowed the gravel pack to settle below the top of the screen, thereby allowing movement of aquifer sand into the screen. The sand produced during redevelopment pumping contains glauconite and Miocene fossil material foreign to the aquifer. There is some evidence that the high injection heads during test 3 may have caused a channel along the boundary of the gravel pack and well screen so that sand and clay from an overlying formation could move downward through the channel into the screen. The younger material is probably best explained by incomplete development pumping during the construction of the well, resulting in drilling mud being left in the gravel pack. The majority of sand production, on the basis of examination of the screen by down-hole television during test 4 withdrawal, appears to be coming from a breach in the gravel pack below a depth of 972 ft (296 m) below sea level.

The obvious question is whether the sand production and resulting clogging could have been prevented if the formation had been treated with clay stabilizers prior to injection of any freshwater. The question cannot be answered definitely unless a new well is drilled. Based on published data and observations made through long exposure to the problems of the injection project, we believe that physical clogging can be minimized provided proper well construction and formation treatment are utilized. X-ray and thin sections of core samples indicate that the consolidation factor is very low and that the bonding agent is essentially the clay surrounding the quartz grains. If dispersion of the clay is prevented prior to injection of freshwater by treatment with trivalent cations, such as aluminum, clogging by sand should be a minor problem in a properly developed well.

The chemical quality of water recovered indicated that the injection and retrieval of freshwater from an aquifer containing brackish water is entirely feasible. During this study, only 15 percent of the injected water was considered not potable according to U.S. Public Health Service standards (chloride more than 250 mg/l). Further, adverse chemical reactions (deterioration in water quality or large scale chemical precipitation) did not occur as a result of injection and withdrawal of the freshwater from the brackish-water sand. The freshwater injected contained no coliform bacteria, and biological contamination was not found in the water withdrawn.

Chemical measurements, such as those for pH and dissolved oxygen, indicated that reactions other than simple silution were occurring when the water was injected. The pH effect was eliminated by pre-treatment of the formation clay with calcium chloride; however, the cause of the loss of dissolved oxygen is unclear at this time.

Laboratory experiments (Kimbler, Kazmann, and Whitehead, 1973) have suggested that the density difference between freshwater and saltwater would cause vertical movement, which could affect the recovery of the injected freshwater. The conductivity profiles and current-meter traverses made in this investigation suggest that under injection conditions the flow was essentially horizontal. Natural stratification within the aquifer may prevent upward migration of freshwater, but not enough evidence is available, especially regarding long-term storage under static conditions, to warrant any conclusions. Also, the effect of injection on the natural movement of water could not be fully evaluated. The injected water was not left in residence long enough and the observation-well network was not dense enough to observe the effect, if any,,injection has on the movement of formation water.

An injection well field at Moore's Bridges Filter Plant, ideally, would have at least 4 wells; each capable of injecting 1,000 gal/min (63 l/s) and withdrawing 2,000 gal/min (126 l/s). Injection would be continuous until a sufficient quantity had been injected so that withdrawal demands would not remove more than 60 percent of the injected freshwater.

Invasion of drilling fluids into the sediments usually occurs during hydraulic rotary drilling. In a withdrawal well this is normally not a problem, but in an injection well, where clay dispersion is a possibility and prevention of clogging is essential, invasion of drilling fluids can jeopardize the life of the well. Therefore, to minimize the invasion of drilling mud into the aquifer, a proposed injection zone could be drilled using a hydraulic reverse rotary method.

The Norfolk study has shown that clogging of the formation by iron precipitation is not sufficient to prevent the use of steel casing, although a stainless-steel screen would probably be required because of the brackish water. If a different aquifer or well field location were chosen, then new calculations of the iron reactions would have to be made. The advantages or disadvantages of a gravel pack have been widely published for withdrawal wells, but, because of the serious problems that can be caused by clogging in the gravel pack of an injection well, natural completion (no gravel pack) using a wire-wrapped screen may help to minimize clogging problems. A screen with a round or square wire, rather than a V-shape, may reduce internal clogging.

To effectively inject 1,000 gal/min (63 l/s) and withdraw 2,000 gal/min (126 l/s), the specific capacity of an injection well would be in the range of 20 to 30 gal $min^{-1}ft^{-1}$ or 4.1 to 6.2 $ls^{-1}m^{-1}$. In the Norfolk area, in order to obtain a specific capacity within that range at the proposed pumping rates, more screened aquifer is required than was used in IW-2. Test drilling in the vicinity of IW-2 has shown that the sand from approximately 750 to 1,000 ft (229 to 305 m) below land surface and the chemical quality of the water in this interval are rather uniform. Using electric-log and core-sample data to determine screen placement, this entire section could be selectively screened in order to obtain the desired specific capacity.

Immediately after setting the screen, development pumping exceeding maximum operational rate would continue until sand pumping ceased. At this time treatment of the formation to prevent clay dispersion would begin—before freshwater is introduced into the well. The detailed method of treatment is available from several oil field service companies.

The design of an injection well would be more efficient than that of IW–2 if the same size casing extended from the surface to the top of the screen. This would allow the installation of additional pump column and provide for greater drawdown. With such construction, the screen may be adjusted or even removed and replaced if necessary. The design also could provide access for a current meter in order that changes in the injection flow pattern from that of the pre-injection pattern could be detected.

Withdrawal pumps on the first injection well would be capable of pumping at least 2,000 gal/min (126 l/s) against a total dynamic head of 300 ft (91 m). Aquifer-test data could then be used to refine pump requirements for subsequent wells. The only special construction requirement for a withdrawal pump would be to have stainless-steel line-shaft, epoxy-coated column pipe, and an all-bronze bowl assembly. Each well would be equipped with its own injection pump located at the freshwater collection point. The injection pump would be capable of pumping more than 1,000 gal/min (63 l/s) against a total dynamic head of 120 ft (37 m). The water injected, ideally, would contain the least possible amount of particulate matter.

Spacing in a well field is normally based on hydraulic characteristics of the aquifer in that the wells are spaced far enough apart to prevent serious hydraulic interference when several wells are pumping. In an injection well field,

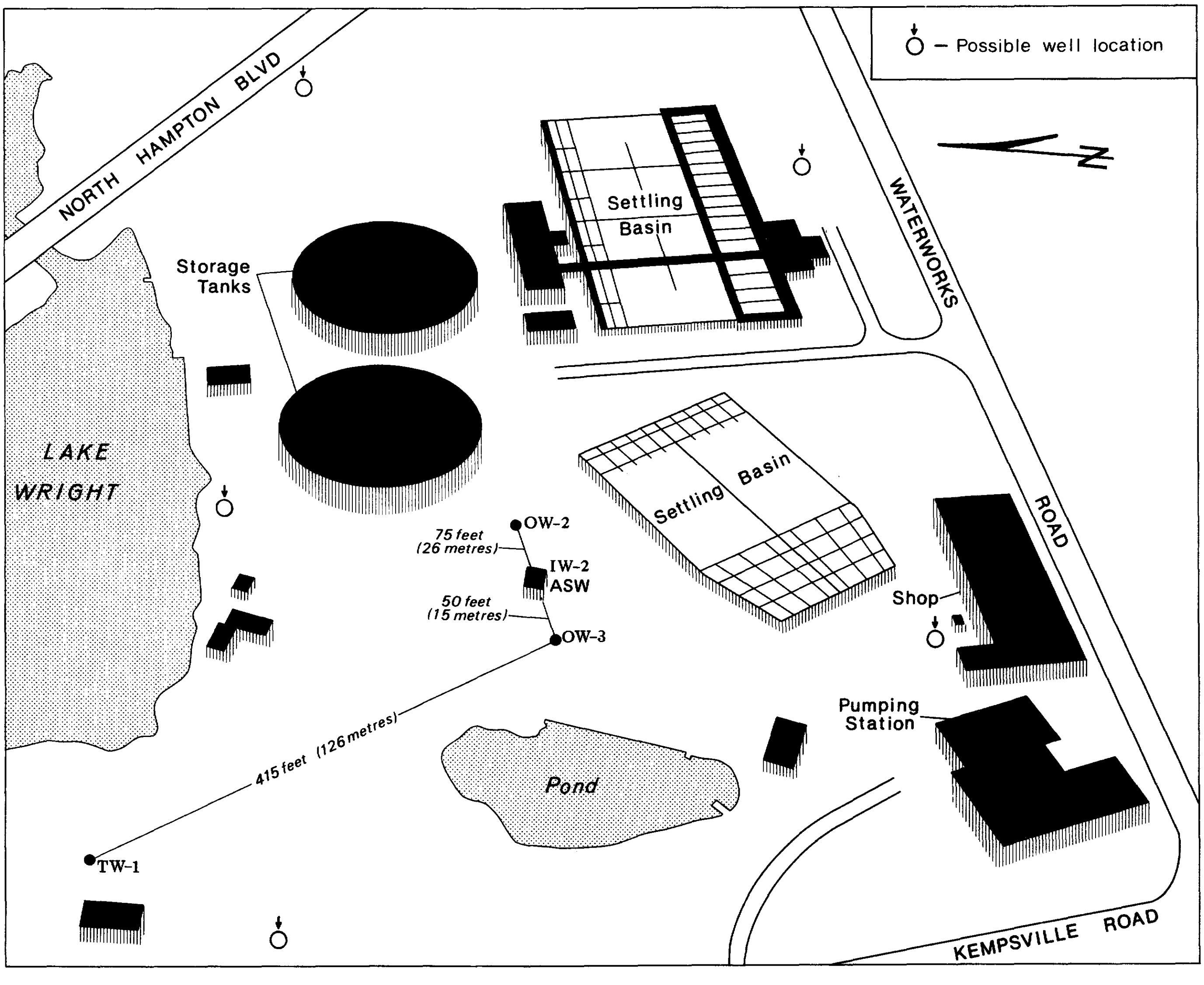


FIGURE 39.—Possible well locations for a five-well injection field at Moore's Bridges Filter Plant.

however, two additional considerations are of equal importance: (1) The distance from the source for injection water, and (2) the shape of the injection front.

Injection tests 2 and 4 demonstrated that the spread of water from the injection well is non-radial and is elongated roughly in a northwest direction. Wells placed perpendicular to the long axis of the injection front in the shape of an expanded W, with a minimum of 600 ft (183 m) between the wells, would make efficient use of space available (at the Filter Plant for instance) and the hydraulic properties of the aquifer could be achieved (fig. 39). This spacing and well configuration would only apply to the area under investigation. If a well field were to be located in a different area, an analysis of the hydraulic properties of the aquifer at that location would be necessary. Using this spacing, and assuming an aquifer thickness of 150 ft (46 m), approximately 100 Mgal (378,000 m^3) of freshwater could be stored by each well in the area of the Filter Plant before well interference became serious.

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