Preliminary Results of Injecting Highly Treated Sewage-Plant Effluent Into a Deep Sand Aquifer at Bay Park, New York

GEOLOGICAL SURVEY PROFESSIONAL PAPER 751-A

Prepared in cooperation with the Nassau County Department of Public Works

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By JOHN VECCHIOLI *and* HENRY F. H. KU

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CONTENTS

ILLUSTRATIONS

TABLES

DEEP-WELL ARTIFICIAL RECHARGE EXPERIMENTS AT BAY PARK, LONG ISLAND, NEW YORK

PRELIMINARY RESULTS OF INJECTING HIGHLY TREATED SEWAGE-PLANT EFFLUENT INTO A DEEP SAND AQUIFER AT BAY PARK, NEW YORK

By John Vecchioli and Henry F. H. Ku

ABSTRACT

Highly treated sewage-plant effluent is being injected into a sand aquifer at Bay Park, N.Y. Recharge is through a fiberglass-cased well finished with a gravel-packed 16-inch diameter stainless-steel screen set between 418 and 480 feet below land surface. The well is open to the Magothy aquifer of Late Cretaceous age. Maximum recharge rate thus far is 360 gallons per minute.

Head buildup in the injection well (but not the aquifer) in each injection test has exceeded that predicted by pumping-test data even though the water injected had a physical and chemical quality acceptable for drinking water. In one test, the specific capacity of the injection well was reduced to half the preinjection value after 10 days of injection. Excessive head buildup is strongly dependent upon the turbidity of the recharge water, even though turbidity levels are generally less than 2 milligrams per liter as SiO_2. The fine-grained nature of the aquifer probably accounts for the well's high sensitivity to small amounts of suspended matter.

Redevelopment by pumping after each injection test has resulted in restoration of most of the specific capacity prevailing prior to each test. The first slug of water recovered during redevelopment is very turbid and the concentrations of iron, phosphate, and volatile solids are many times greater than those of the injected water. Bacterial content is also many times greater and this together with other evidence suggests that some deterioration in well capacity may be a result of biologic clogging.

INTRODUCTION

PURPOSE AND SCOPE

Nassau County is a highly urbanized area on Long Island adjacent to New York City (fig. 1). Its population has grown from 672,765 in 1950 to almost 1.5 million in 1965 (Peters and Rose, 1968, p. 627). With the growth of population has come a steady increase in ground-water pumpage for public supply—to nearly 210 mgd (million gallons per day) in 1965 (Cohen and others, 1968, p. 70). Pumpage is expected to be almost 300 mgd by 2010 (Peters and Rose, 1968, p. 627). Local ground water presently is the only source of public-supply water, with most of the water being obtained from the Magothy aquifer of Late Cretaceous age. Intensive net withdrawals from that aquifer have

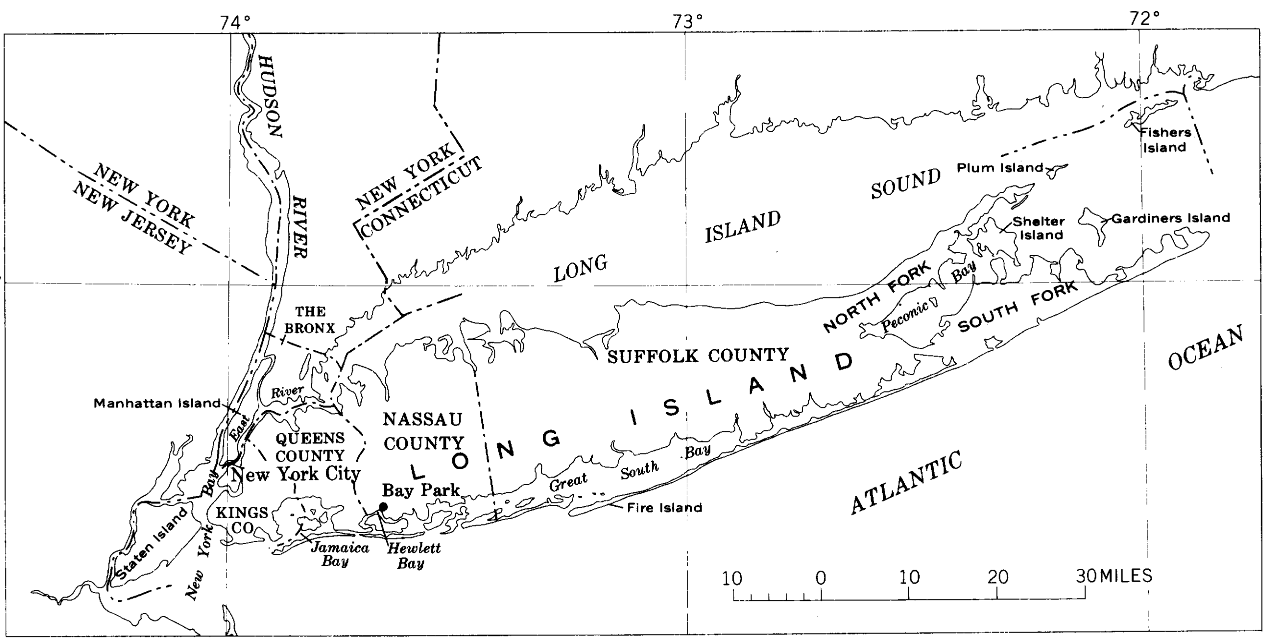

FIGURE 1.—Location of Bay Park injection site.

resulted in local landward movement of salty ground water (Lusczynski and Swarzenski, 1966; Cohen and Kimmel, 1970), and anticipated increased net withdrawals may accelerate the encroachment of salty ground water into Long Island's aquifers.

A conservation method currently under study by Nassau County involves the reclamation of waste water and its return to the aquifer. Return might be through coastal injection wells intended to create a hydraulic pressure ridge and thus stabilize or retard movement of the salt-water front; or it might be through inland recharge basins or wells intended to augment natural recharge to the aquifers (Peters and Rose, 1968, p. 625).

As part of the water-reclamation study, the U.S. Geological Survey in cooperation with the Nassau County Department of Public Works is conducting a series of artificial-recharge experiments at Bay Park, N.Y. These tests are intended to obtain some of the scientific and economic data needed to evaluate the feasibility of injecting highly treated sewage-plant effluent into a proposed network of barrier-injection wells.

The water-reclamation process, briefly, is as follows (Peters, 1968, p. 33). About 0.6 mgd of the effluent from an activated-sludge type sewage-treatment plant is given tertiary-stage treatment. This process consists of coagulation and sedimentation followed by filtration, first through a dual-media sand-anthracite filter and then through one to four activated carbon columns. Chlorination is the final step in the treatment. The reclaimed water produced by this process meets commonly accepted potable-water standards (Public Health Service, 1962). Additional treatment including degasification, pH adjustment, and dechlorination can be applied at the injection plant.

Recharge takes place through a gravel-packed well consisting of an 18-inch diameter fiberglass casing above a 16-inch diameter stainless-steel screen, which is set 418 to 480 feet below land surface (Cohen and Durfor, 1966). Initially, the long-term pumping specific capacity of this well was about 33 gpm (gallons per minute) per foot of drawdown (G. D. Bennett, written commun., 1968). The injection stratum, which lies within the Magothy aquifer, consists mostly of slightly silty fine to medium sand with thin beds of coarse sand. The static water level of the injection stratum is about 5 feet below land surface, fluctuating generally between about 4 and 6 feet below the surface.

This progress report presents preliminary conclusions reached from the testing done to date with the treated sewage-plant effluent. Experimental recharge with sewage-plant effluent has been underway since October 1968. As of December 1969, three injection tests of 2-days duration and two of 10-days duration have been made. The recharge rate has varied from 200 to 360 gpm. The recharge water has been degasified in three of the tests. Table 1 summarizes significant features of the tests.

PREVIOUS WORK

The water-treatment and injection facilities at Bay Park have been described in several reports. Cohen and Durfor (1966) presented a detailed description of the injection well. In another paper, Cohen and Durfor (1967) discussed the objectives of the recharge study, and they briefly described the injection equipment. Peters and Rose (1968) reported extensively on the overall project with particular emphasis on the water-treatment facilities. Peters (1968) commented on the overall project, including some discussion of early operations of the treatment and injection plants. The geology and hydrology of the Bay Park site as well as the injection facilities and the nature of the experimentation were discussed briefly by Perlmutter, Pearson, and Bennett (1968). G. D. Bennett and others (written commun., 1969) described in detail the geohydrology, aquifer and well hydraulics, and the hydrochemistry of the injection site. F. J. Pearson, Jr. and G. D. Bennett (written commun., 1969) reported on results of early injection experiments that utilized public-supply water.

ACKNOWLEDGMENTS

The authors are especially grateful to John H. Peters, Commissioner, Nassau County Department of Public Works, for making available the physical and human resources of the Department throughout the course of this project. Particular thanks are given also to Francis J. Flood, Superintendent of Maintenance and Operations, Nassau County Department of Public Works, and to many others in that department for coordinating water-treatment operations with the injection experiments and for providing assistance in making modifications to the injection equipment.

Maxim Lieber of the Nassau County Department of Health provided many of the chemical and all the bacteriologic analyses used in this study. Joseph H. Baier of the Nassau County Department of Health rendered much advice in planning the bacteriologic

TABLE 1.—*Injection-test statistics*

Test No.	Date	Approximate length (days)	Injection rate (gpm)	Gallons injected	Treatment at injection plant
RW1 [1]	Oct. 8–10, 1968	2	200	616,000	Degasification.
RW2	Dec. 10–12, 1968	2	350	1,063,000	Do.
RW3	Feb. 25–27, 1969	2	350	1,066,000	None.
RW4	May 6–16, 1969	10	360	5,247,000	Do.
RW5	Sept. 15–25, 1969	10	350	5,117,000	Degasification.

[1] RW signifies "renovated water."

sampling program. John L. Rose and James Oliva of Burns and Roe, Inc., consulting engineers, participated in numerous helpful discussions. Louis S. Guaracini, Nassau County Department of Public Works, made some chemical analyses and also offered advice on numerous occasions regarding chemical problems. Wilbur D. Robichaux, Nassau County Department of Public Works, provided numerous suspended-solids analyses. Thanks are given also to Samuel D. Faust, Rutgers University, for his advice on chemical problems.

This phase of the study was under the general supervision of Garald G. Parker and Robert J. Dingman, respectively former and present district chiefs of the U.S. Geological Survey, Water Resources Division, New York district. Philip Cohen, assistant district chief in charge of the Long Island program provided immediate supervision. Anthony A. Giaimo, Dennis Sulam, and Lillian B. Maclin, U.S. Geological Survey, and Lawrence A. Cerrillo, formerly with the U.S. Geological Survey, assisted in making test measurements and in reducing and compiling the data acquired. The authors are grateful for all this assistance.

QUALITY OF THE WATER INJECTED

The chemical quality of the water injected in each test is given in table 2. In general, the water varied

TABLE 2.—*Selected chemical-quality characteristics of water injected in each test*

[All constituents in milligrams per liter, except pH. Upper figures: Maximum observed–minimum observed. Lower figure: Median]

Analyses by Nassau County Department of Health

Test No. Number of samples	RW1 3	RW2 3	RW3 4	RW4 21	RW5 10
Total iron	0.56–0.23 0.53	0.18–0.08 0.10	0.21–0.04 0.13	0.34–0.02 0.12	0.58–0.14 0.24
Free CO_2	31–19 20	45–26 34	55–36 43	100–36 65	31–15 21
Fluoride	0.34–0.22 0.22	0.32–0.16 0.22	0.39–0.29 0.31	0.44–0.24 0.34	0.45–0.16 0.26
Ammonia nitrogen	26.5–22.5 25	29.5–25.5 28	24.5–21.5 23.2	30–21.5 25	29–23 25
Albuminoid nitrogen	0.53–0.46 0.53	0.60–0.52 0.55	0.54–0.33 0.35	0.52–0.27 0.36	0.56–0.32 0.36
Nitrite nitrogen	0.003–0.001 0.001	0.003–<0.001 0.001	<0.001–<0.001 <0.001	0.001–<0.001 <0.001	0.002–<0.001 <0.001
Nitrate nitrogen	<0.05–<0.05 <0.05	<0.05–<0.05 <0.05	0.25–<0.05 <0.05	1.55–<0.05 <0.05	<0.05–<0.05 <0.05
Oxygen consumed	13–6.8 10	4.8–4.4 4.6	4.6–3.1 3.8	3.9–2.1 3.3	3.4–2 3
Chloride	75–69 70	74–72 72	86–76 78	70–62 64	77–63 73
Total hardness	80–66 72	70–64 68	70–66 69	106–54 62	92–64 72
Total alkalinity	87–84 86	82–76 81	86–78 85	86–33 73	91–68 77
pH	7.0–6.7 6.9	6.8–6.6 6.7	6.7–6.5 6.6	6.6–6.2 6.4	7.1–6.9 7.0
Total solids	364–355 357	376–370 373	380–364 377	418–259 377	377–338 357
Methylene blue active substances	0.41–0.28 0.39	0.59–0.18 0.24	0.14–0.07 0.13	0.18–<0.02 <0.02	0.04–0.02 0.02
Calcium hardness	42–36 38	44–34 38	38–34 35	44–28 34	50–40 42
Total phosphate	3.60–1.90 3.40	3.08–1.0 2.32	2.40–1.74 2.32	4.20–0.90 1.56	6.20–1.44 3.56
Orthophosphate	3.60–1.90 3.40	2.80–0.90 1.92	1.92–1.44 1.91	3.50–0.81 1.52	4.80–1.40 3.10
Sulfate	125–115 118	147–132 144	144–132 135	185–118 147	144–127 137

Analyses by U.S. Geological Survey

Test No. Number of samples	RW1 6	RW2 6	RW3 7	RW4 11	RW5 9
Silica	14–13 14	14–14 14	14–13 14	15–12 14	14–10 14
Calcium	16–15 16	18–16 16.5	16–15 16	18–15 16	18–16 18
Magnesium	6.3–5.2 5.7	5.6–5.3 5.4	5.1–4.7 4.9	4.4–2.7 4.1	5.7–5.0 5.2
Sodium	81–71 76.5	68–66 67.5	86–76 80	77–63 69	74–64 69
Potassium	13–12 12.5	13–12 12	13–12 12	13–12 12	12–11 11

little, chemically, from test to test, and what variations did occur did not appear to be significant controlling factors in the head buildup observed in each test; an exception is the phosphate content of the water injected in test RW5, as discussed in a later section.

The physical quality of the water injected varied to a greater extent than the chemical quality and significantly so, as discussed beyond. Temperature ranged from 14°C (Celsius) in test RW3 to 23°C in RW5 (table 4). Turbidity also showed considerable variation from test to test and during individual tests. Temperature, of course, is largely dependent on the time of year. The turbidity of the recharge water depends upon several factors in the treatment process including influent load, effectiveness of the operation of the clarifier, and backwashing of the filters.

Turbidity of the water injected during the first three tests, as measured by an automatic continuous-recording turbidimeter, is shown in figure 2. Because of questionable operation of this unit during tests RW4 and RW5, it was necessary to measure turbidity by other means. A manually operated turbidimeter was used in the latter tests as well as during test RW3. Comparison of the two methods during test RW3, as well as on a few other occasions, indicates that the turbidity determinations are not identical quantitatively; hence direct comparison of turbidity during tests RW4 and RW5 with turbidity during the earlier tests is not possible.

Turbidity determinations made during tests RW4 and RW5 are plotted in figure 3. During test RW4, the mean turbidity of the injected water was 0.90 mg/l (milligrams per liter) as SiO_2 and the standard deviation was 0.42 mg/l as SiO_2. For test RW5, the mean was 0.57 mg/l as SiO_2 and the standard deviation was 0.33 mg/l as SiO_2. Test of significance at the 95-percent confidence limit showed the means to be significantly different. (See p. A9.)

With the exception of test RW1, bacterial quality of the water injected showed little variation from test to test. Table 3 gives summary data on the bacterial quality of water for each test, as measured by coliform counts.

EFFECTS OF INJECTION ON WELL CAPACITY

CHANGES IN SPECIFIC CAPACITY

The effect of injecting the reclaimed water on the capacity of the injection well can be evaluated in terms

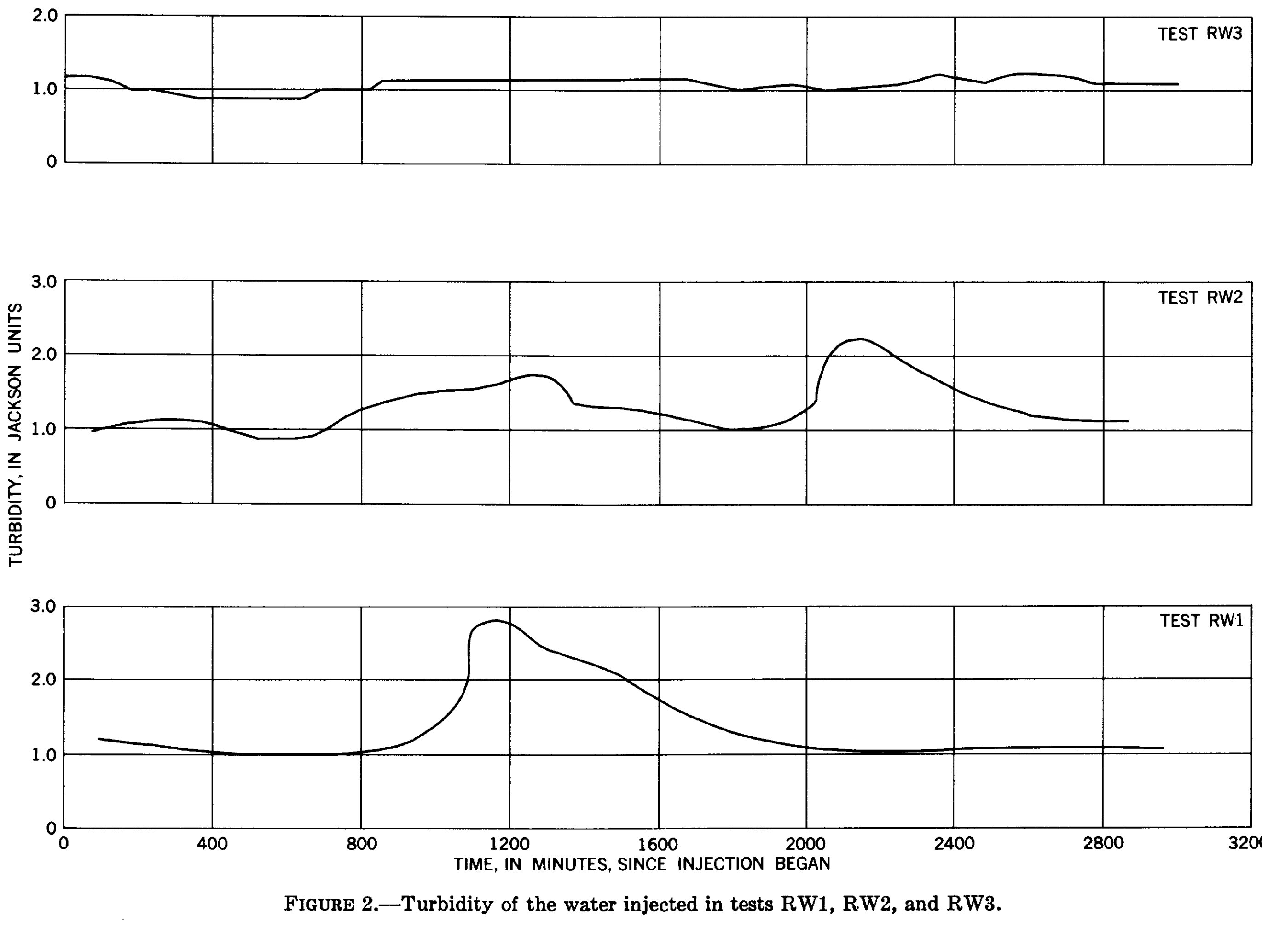

FIGURE 2.—Turbidity of the water injected in tests RW1, RW2, and RW3.

of the specific capacity of the well. When water is withdrawn from a well, the specific capacity of the well is the rate of yield, in gallons per minute, per foot of drawdown; when water is injected into a well, the specific capacity of the well is the rate of injection per foot of head buildup. If no well clogging occurs, the head buildup observed in the well during injection should theoretically equal the drawdown that would occur if the well were pumped at the same rate, other things being equal. Head buildup in excess of that amount is an indication of clogging of the well and (or) the aquifer, and the excess buildup is reflected in a decrease in the injecting specific capacity of the well.

Before any injection, the long-term (2 days) pumping specific capacity of the well was 32.8 gpm per foot (G. D. Bennett, written commun., 1968). However, the pumping specific capacity decreased as a result of the recharge operations, and the pumping specific

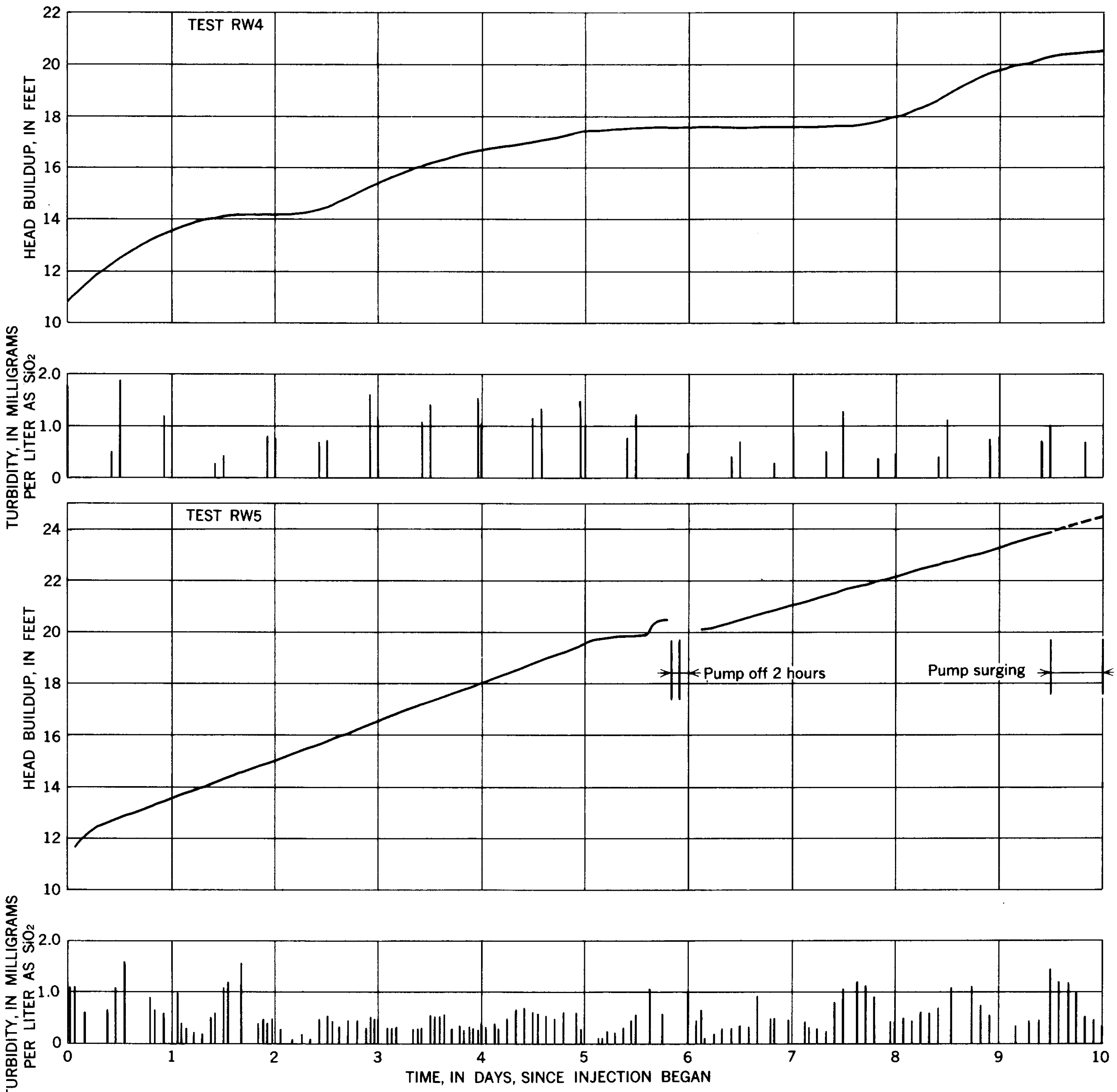

FIGURE 3.—Head buildup and turbidity of water injected in tests RW4 and RW5.

capacity before each injection test has, in general, been slightly less than the pumping specific capacity before the preceding test (table 4).

The injecting specific capacities observed in each injection test were lower than the corresponding pumping specific capacities obtained before each test. This indicates that some clogging of the well and (or) the contiguous part of the aquifer occurred in each injection test. Specific capacity data are summarized in tables 4 and 5.

Head buildup distribution in the aquifer at distances of 20 to 200 feet from the injection well was virtually equal, in each injection test, to the drawdown distribution observed during the original pumping test. Hence clogging of the aquifer, if any occurred, probably was restricted to the immediate vicinity of the injection well.

Temperature of the water injected varied from test to test. Because (1) the viscosity of the water is inversely related to temperature, (2) the hydraulic conductivity is inversely related to the viscosity of the water, and (3) the specific capacity of the well is

TABLE 3.—*Bacterial quality of water injected in each test*

[Bacterial analyses by Nassau County Department of Health]

Test No.	RW1	RW2	RW3	RW4	RW5
Total chlorine, residual (mg/l):					
Maximum observed	—	2.2	3	3.5	3
Minimum observed	—	0	0	2	2
Median	—	1.2	2.5	2.5	2.5
Number of samples	—	25	14	33	30
Coliform confirmed (MPN[1]/100ml):					
Maximum observed	>240	38	2.2	5	38
Minimum observed	2.2	<2.2	<2.2	<2.2	<2.2
Median	93	2.2	<2.2	<2.2	<2.2
Number of samples	23	25	15	33	31
Standard plate count at 35°C (number/ml):					
Maximum observed	>300	64	<30	35	<30
Minimum observed	<30	<30	<30	<30	<30
Median	>300	<30	<30	<30	<30
Number of samples	23	25	15	33	31

[1] Most probable number.

TABLE 4.—*Unadjusted and adjusted 2-day specific capacities for each injection test*

Test No.	(1) Pretest 2-day pumping specific capacity (gpm/ft)	[1] (2) Unadjusted 2-day injecting specific capacity (gpm/ft)	(3) Apparent decrease in specific capacity; col. 1 − col. 2 (gpm/ft)	(4) Temperature (°C)	(5) Head-buildup correction (ft)	(6) Adjusted 2-day injecting specific capacity (gpm/ft)	(7) Adjusted decrease in specific capacity; col. 1 − col. 6 (gpm/ft)
RW1	31.7	28.6	3.1	22	+0.50	26.7	5.0
RW2	30.4	27.4	3	16	+ .14	27.1	3.3
RW3	30.5	30.3	.2	14	− .14	30.6	---
RW4	30.3	25.6	4.7	18	+ .44	24.8	5.5
RW5	28.9	22.9	6	23	+1.01	21.5	7.4

[1] Column 2 represents specific capacity based on head buildup unadjusted for differences in temperature of the injected water and the native aquifer water (15°); column 5 is adjustment for temperature difference; and column 6 is specific capacity based on adjusted head buildup.

TABLE 5.—*Unadjusted and adjusted 10-day specific capacities for tests RW4 and RW5*

Test No.	(1) Pretest 10-day pumping specific capacity (gpm/ft)	[1] (2) Unadjusted 10-day injecting specific capacity (gpm/ft)	(3) Apparent decrease in specific capacity; col. 1 − col. 2 (gpm/ft)	(4) Temperature (°C)	(5) Head-buildup correction (ft)	(6) Adjusted 10-day injecting specific capacity (gpm/ft)	(7) Adjusted decrease in specific capacity; col. 1 − col. 6 (gpm/ft)
RW4	30.3	17.7	12.6	18	+0.53	17.2	13.1
RW5	28.9	14.7	14.2	23	+1.21	14	14.9

[1] Column 2 represents specific capacity based on head buildup unadjusted for difference in temperature of the injected water and the native aquifer water; column 5 is adjustment for temperature difference; and column 6 is specific capacity based on adjusted head buildup.

closely related to the hydraulic conductivity of the aquifer, adjustments need to be made in the specific capacity to account for the temperature differences. These adjustments were made by a method described by G. D. Bennett (written commun., 1969) in which the extent of the cylinder of injected water of temperature different from that of the aquifer water is taken into consideration. Bennett's method is as follows. The head-buildup correction at any time caused by the temperature difference is calculated from the equation

$$s_{wTt} - s_{wt} = \left(\frac{1}{K_{LT}} - \frac{1}{K_L}\right)\frac{2.3Q}{2\pi D}\log\left(\frac{r_{Tt}}{r_w}\right) \quad (1)$$

where $s_{wTt} - s_{wt}$ = head buildup in the injection well for injection water of temperature T, at time t, minus head buildup in injection well for formation water at time t, in feet.

K_{LT} = lateral hydraulic conductivity to injection water of temperature T; in feet per day.

K_L = lateral hydraulic conductivity to formation water, in feet per day.

Q = injection rate in cubic feet per day.

D = thickness of injection stratum, in feet.

r_{Tt} = radius of cylinder of injection water of temperature T, at a time t after the start of injection, in feet., and

r_w = radius of injection well, in feet.

The lateral hydraulic conductivity of the formation to injection water at temperature T, K_{LT}, is obtained by multiplying the hydraulic conductivity to formation water, K_L, by $\frac{\mu}{\mu_T}$ where μ is the viscosity of the formation water and μ_T is the viscosity of the injection water.

In applying the temperature adjustments, several simplifying assumptions must be made that are known not to be entirely valid. Hence the adjustments to the specific capacities as given in tables 4 and 5 represent extreme values, and the actual adjustments probably should be somewhat less. Accordingly, the true specific capacity probably lies somewhere between the observed value and the adjusted value.

EFFECT OF TURBIDITY ON EXCESSIVE HEAD BUILDUP

A causal relation has been observed between the turbidity of the injected water and the excessive head buildup in the injection well. The excessive head buildup is simply an expression of the clogging of the well. Without clogging, the head buildup should virtually stabilize at the end of about 1 day owing to the leaky artesian character of the aquifer (G.D. Bennett, written commun., 1969). (See fig. 4.) After adjustments are made for temperature differences, any increase in head buildup beyond that predicted by the pumping test curve represents a decrease in the injecting specific capacity of the well caused by clogging.

It was noted that turbidity varied from test to test and within individual tests; however, directly comparable data are available for only the first three tests. Recalling figure 2, it is seen that turbidity during test RW3 was lowest and comparatively uniform throughout the test. During test RW1, a treatment-plant malfunction resulted in the injection of high-turbidity water for several hours of the test. Turbidity of the water during the second test was generally greater, although the peak concentration was less than the peak concentration of the first test.

The unit head buildup (head buildup divided by rate of recharge) observed in the 2-day tests is shown in figure 4. Also shown is the pumping-test curve representing the unit drawdown (drawdown divided by rate of discharge) observed during pumping of the well prior to any injection; this drawdown curve serves as a reference curve against which to compare the head-buildup curves. If clogging had not occurred during injection, the head-buildup curves should resemble the pumping-test curve, and they do for the first few hours of each test. The later parts of the curves, from about 300 minutes on, depart distinctly from the pumping-test curve. The excessive head buildup shown by the later parts of the curves seems to reflect the turbidity of the injected water closely. The least turbid water injected was that during test RW3, and this test had the least excessive head buildup. The most turbid water injected was that during test RW2 and, correspondingly, this test had the greatest excessive head buildup.

These data are not adjusted to reflect differences in temperature between the injected water and the native aquifer water. However, the only test in which the temperature of the injected water differed significantly was test RW1, in which the injected water was 7°C warmer than the aquifer water. If the final head buildup in test RW1 is adjusted for temperature, the head buildup is raised to about that in test RW2.

Mention should be made also of the initial higher position of the curve for test RW3; this probably re-

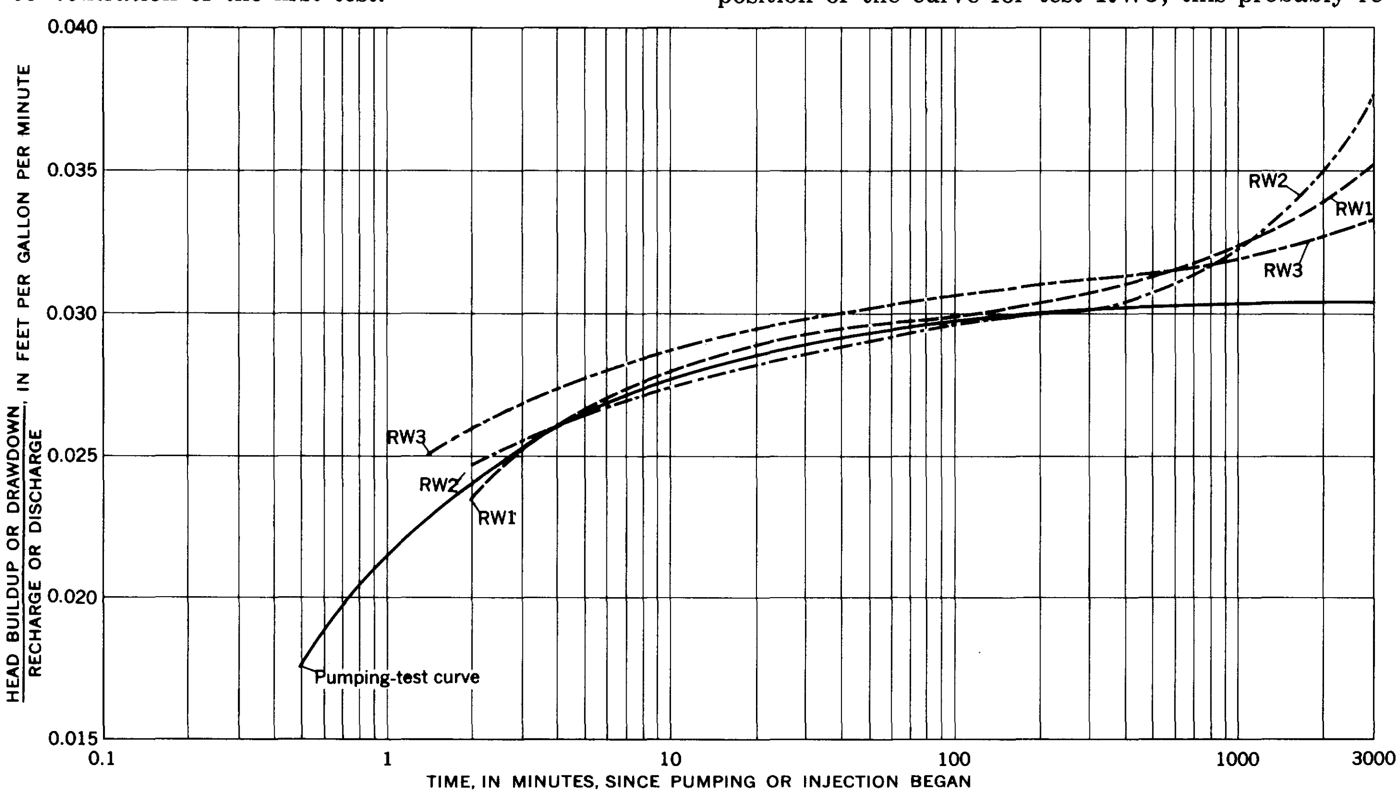

FIGURE 4.—Head buildup in tests RW1, RW2, and RW3 compared to drawdown observed during pumping test made before any injection.

flects, in part, residual deterioration of specific capacity from previous injection tests (table 4).

Another demonstration of the control of turbidity on excessive head buildup is shown by the records for the first 10-day test, RW4 (fig. 3). The pumping-test curve in figure 4 shows that without clogging the head buildup in the injection well should virtually level off by the end of the first day. However, the head buildup in test RW4 (fig. 3) continued to rise irregularly throughout the 10-day period. Comparing the head-buildup curve with the turbidity of the water injected, it is seen that the rate of excessive head buildup (that beyond the first day) is steepest for those periods of injection with relatively high turbidity water, whereas the rate of excessive head buildup diminishes greatly during periods of injection of low-turbidity water.

Head buildup and turbidity data for test RW5 also are shown in figure 3. The control of turbidity on excessive head buildup is not obvious in this test. Apparently another factor was operative in controlling excessive head buildup during this test. (See following discussion on p. A9.)

Turbidity, of course, is a rough measure of the suspended-solids content of the water. For test RW3, the test in which turbidity was lowest (0.3–0.8 mg/l as SiO_2), the suspended-solids content ranged from 2 to 4 mg/l and averaged 3 mg/l; during test RW4, in which the turbidity was as high or higher (0.3–1.85 mg/l as SiO_2) than in any other test except for the peak turbidity in test RW1, the suspended-solids content ranged from 3 to 10 mg/l and averaged 5 mg/l. These suspended-solids contents are very low values, and yet a change of only a few milligrams per liter of suspended matter seems to have an appreciable effect on the excessive head buildup in the injection well.

After each injection test, the well was redeveloped by pumping. The first slug of water recovered each time was very turbid, which probably indicates that most of the injected particulate matter was retained in the immediate vicinity of the well. Turbidity dropped off sharply with continued pumping. Head measurements made in an observation well screened within the gravel pack were virtually identical to those in the injection well, suggesting that the filtration and deposition of the suspended matter was taking place beyond the gravel pack. Presumably, the suspended matter in the injected water was being filtered out at or near the gravel pack-aquifer interface. The fine- to medium-grained character of the injection stratum seemingly is very effective in filtering particulate matter from the injected water. The fineness of the bed probably also accounts for the well's high sensitivity to small amounts of suspended matter.

EFFECT OF DEGASIFICATION ON EXCESSIVE HEAD BUILDUP

Well-clogging problems caused by the release of entrained air or dissolved gases from the injected water have been reported by several investigators (Price, 1961, p. 28; Foxworthy and Bryant, 1967, p. 18; Sniegocki, 1963, p. 4; and California State Water Pollution Control Board, 1954, p. 165). Release of air or gases can cause clogging of the aquifer. Also, excessive amounts of free oxygen can cause precipitation of solutes, such as iron, by changing the oxidation-reduction conditions prevailing in the aquifer.

Of the five tests described in this report, the recharge water was degasified in two of the short tests and in one of the longer tests. Contrary to expectations, the excessive head buildup in those tests was higher than in those tests in which the water was not degasified. Of course, other parameters, such as turbidity, varied from test to test, and this probably was one of the major controls on the excessive head buildup. Hence, if degasification played a role in reducing excessive head buildup it was very minor and not discernible because of masking by the other variables.

Degasification was effective in removing most of the dissolved oxygen and much of the dissolved carbon dioxide from the recharge water and, presumably, any other gases that it contained. For example, in test RW5, prior to being degasified the recharge water contained 4.8 mg/l dissolved oxygen; after it was degasified the dissolved-oxygen content dropped to about 1 mg/l or less. No other significant change in the chemistry of the injection water due to degasification was noted except for an increase in pH, which resulted from the reduction in carbon dioxide content of the water.

Degasification may reduce excessive head buildup over longer periods of injection. However, the short testing accomplished thus far suggests that any such reduction might be small compared to effects of other parameters, contrary to what has been reported from the studies cited above. Apparently the Bay Park system permits little air entrainment when the water is injected under pressure through a pipe which opens into the well casing at a depth of 192 feet (Cohen and Durfor, 1966), as has been done in all the tests thus far. Also, because the temperature of the recharge water has been about equal to or warmer than the aquifer water, any gases dissolved in the recharge water would tend to remain in solution within the higher pressure-colder temperature aquifer environment.

The amount of dissolved oxygen contained in the recharge water is well below saturation. Moreover, the injection water has an organic oxygen demand that probably consumes most if not all the free dissolved oxygen. Hence, the oxidation-reduction regimen within the aquifer is probably not changed sufficiently to cause oxidation of ferrous iron to ferric iron and subsequent precipitation within the aquifer. In fact, the converse appears to be true in that the dissolved ferrous iron content of the injected water increases within the aquifer suggesting a dissolution of iron rather than a precipitation. (See p. A12.)

Facilities at Bay Park allow for the injection of water into the well casing at land surface. Some entrainment of air and (or) an increase in dissolved-oxygen content may result from such a procedure, to the point where well clogging could be affected by those two factors; however, this premise must await future testing.

BIOLOGIC CLOGGING OF THE WELL AND AQUIFER

Clogging of wells by growths of iron bacteria and other slime-producing organisms is a well-known phenomena (anonymous, 1966, p. 196). Direct evidence of such phenomena at Bay Park is not available, but several lines of indirect evidence suggest the possibility of such occurrences. For example, the recharge water, being treated sewage, contains abundant biota-sustaining nutrients. Proliferation of at least coliform bacteria around the injection well has been observed. High concentrations of iron, phosphate, and organic material in the immediate vicinity of the injection well also have been observed. Head buildup in test RW5 is not readily explained by other factors, such as turbidity. In test RW5 the water had the warmest temperature—23°C, dissolved oxygen was removed, the pH was close to neutral, and the phosphate content was highest; all of which provide for favorable environmental conditions for growth of anaerobic organisms. Moreover, treatment of the injection well after test RW4 with a compound designed to control growth of nuisance organisms resulted in a small improvement in well capacity. This treatment suggests that some of the loss in capacity observed during this injection test was a result of biologic clogging.

In most of the tests, a total chlorine residual of 2.5 mg/l was maintained in the injection water. Seemingly, this high residual-chlorine content should have minimized biologic clogging, and perhaps it did. However, because of the high ammonia nitrogen content of the injection water, most of the available chlorine is combined rather than free and, hence, it is a much less efficient colicidal agent (Fair and Geyer, 1954, p. 808). In addition, no chlorine residual has been observed in water from an observation well 20 feet away from the injection well, which indicates that the available chlorine does not persist for long within the aquifer. Besides the organic material injected, the aquifer contains carbonaceous matter, such as lignite, which would readily absorb chlorine.

In summary, clogging of the well and the adjacent aquifer by bacterial growths is an unanswered problem at this time, but certainly the importance of the problem warrants continued, more detailed bacterial studies.

RATE OF EXCESSIVE HEAD BUILDUP

It is somewhat premature to comment on the long-term rate of excessive head buildup because the injection tests thus far have not exceeded 10 days. However, from figure 3, it is seen that the rate of excessive head buildup insofar as has been observed, appears to be roughly linear on an arithmetic scale. For test RW4, the average rate over the 10-day period was about 0.75 of a foot per day. In test RW5, a rate of 1.5 feet per day prevailed for the first 5 days and a rate of slightly more than 1 foot per day prevailed for the latter 5 days. The change in rate may in part be due to a 2-hour unscheduled shutdown of the pump on the sixth day.

If one assumes that the rate of excessive head buildup will remain roughly linear over longer periods of time, and if an excessive head buildup of 100 feet is taken as an arbitrary allowable limit, then, at a rate of about 1 foot per day, periods of uninterrupted injection could extend for only 100 days. At that time, injection would have to be halted temporarily and the well redeveloped. Of course, if higher excessive injection heads were allowed, continuous injection could proceed for longer periods. The amount of allowable excessive head buildup would depend upon, among other things, the nature and thickness of material overlying the injection zone immediately adjacent to the well and the design of the injection well and appurtenances.

Future injection experiments of up to several months duration are planned to test the long-term rate of excessive head buildup.

RESTORATION OF WELL CAPACITY

After each injection test the well was redeveloped by pumping. Thus far, the specific capacity that prevailed prior to each test was largely but not entirely restored. Residual deterioration that occurred, particularly after tests RW1, RW4, and RW5, has resulted in a 20-percent cumulative decline of the pumping specific capacity of the well from that prior to any injection with treated sewage.

Most of the well-capacity restoration occurred within the first hour or so of pumping, when the bulk of the suspended solids that had been injected were removed. Additional restoration doubtlessly occurred whenever the pumping rate was increased abruptly, or pumping was stopped and restarted, owing to the removal of additional particulate matter with each surge. After the first few surges, the well capacity restored with each successive surge was small.

After test RW4, redevelopment by continuous pumping at varying rates was carried out for 5 days. The well was then surged 10 times by pumping it at 1,000 gpm, the maximum capacity of the equipment, for 10-minute intervals followed by 5-minute shutdown periods. No improvement in specific capacity was noted. This procedure was repeated after 2 days of continuous pumping; this time 20 surge-cycles were applied. Again no noticeable improvement occurred. Another 10 surge-cycles were applied 2 days later, again with no apparent improvement.

After redevelopment by pumping was considered complete, the well was dosed with a solution of a commercial ammonium compound designed to control the growth of nuisance organisms in wells. The well was then pumped and a carefully controlled specific-capacity test was made. The test indicated an improvement of about 7 percent in the specific capacity over that prevailing before the treatment.

QUALITY OF INITIALLY REPUMPED WATER

After each recharge test, the injection well was pumped to remove the water injected and, also, to attempt to restore the specific capacity of the well. With the exception of test RW3, the first water recovered was invariably highly turbid and contained concentrations of suspended solids, iron, and phosphate many times greater than those of the injected water. (See table 6.) Much of the suspended solids were volatile solids and this, coupled with the high oxygen demand of the water, indicates that much of the material that accumulated around the well was organic. Moreover, after at least three of the tests, the first water pumped was slightly higher in ammonia nitrogen and albuminoid nitrogen than the injected water. Also, the water at first was unpleasantly odorous, suggesting the presence of dissolved gases, which may be a result of organic decomposition.

TABLE 6.—*Selected physical- and chemical-quality parameters of initially recovered water*

[Analyses by Nassau County Department of Health. All constituents in milligrams per liter]

Test No.	RW1	RW2	RW3	RW4	RW5
Turbidity	225	78	5	80	[1] 163
Total phosphate	30	26	1.44	19.6	43.5
Total iron	45.5	7.55	.08	15.1	50.5
Total solids	672	513	—	532	686
Total suspended solids	328	136	6	84	248
Total dissolved solids	344	377	381	448	438
Total volatile solids	171	146	—	132	232
Volatile suspended solids	116	50	—	37	82
Volatile dissolved solids	55	96	—	95	150
Total fixed solids	501	367	—	400	454
Fixed suspended solids	212	86	—	47	166
Fixed dissolved solids	289	281	—	353	288
Oxygen consumed	[2] 48	35	15	36	[1] 21

[1] Sample collected 5 minutes later than others.
[2] Analysis for total organic carbon.

The turbidity and associated high values of suspended solids, phosphate, and iron content prevailed during the first few tens of minutes of pumping. With continued pumping, they gradually diminished to low values, but, upon an abrupt increase in pumping rate or upon a shutdown and subsequent renewal of pumpage, turbidity increased once again. In other words, everytime the velocity of the water moving into the well was increased abruptly, the resulting agitation dislodged particles that had been filtered or adsorbed onto the aquifer face during injection. Each succeeding agitation resulted in a lesser amount of material being dislodged than in the previous one until virtually no more injected material was dislodged.

Much the same can be said for the bacterial content of the recovered water. After each test, the injection well was left idle for 4 to 20 days. The well was then pumped intermittently until practically all the recharge water was extracted and the well was once again producing virtually native ground water. In each instance, high counts of coliform bacteria were observed in the first water recovered. Continued pumping resulted in lower counts. However, whenever the well was idled, the water that was initially recovered upon resumption of pumping, after the casing was cleared, contained a higher bacterial count than before the end of the previous pumping period. This may have been due in part to a growth of organisms during the idle periods, to a dislodging of a greater number of organisms owing to the surging action at the start of pumping, or to a combination of both. Data for test RW4 is given in table 7; the trend shown typifies that observed after each of the tests.

MOVEMENT OF INJECTED WATER THROUGH THE AQUIFER

DISPERSION OF THE FRONT

Because the dissolved-solids content of the injected water is about 10 times greater than that of the native aquifer water, specific conductance provides a convenient parameter for monitoring the movement of the injected water within the aquifer. Conductivity of the injected water ranged from about 700 to 800 micromhos, whereas the conductivity of the native aquifer water was about 40 micromhos. Conductivity of water from an observation well 20 feet away (N7886) from the injection well and a well 100 feet away (N7890) during injection tests RW4 and RW5 are plotted in figure 5. Conductivity of the water from well N7886 was determined from pumped samples and, because this observation well is screened the full thickness of the

TABLE 7.—*Bacterial quality of water recovered after test RW4 in 1969*

[Analyses by Nassau County Department of Health. Intermittent pumping from 6-5 to 6-23; pauses from 6-27 to 7-1, 7-1 to 7-15, 7-16 to 8-6]

Date	Cumulative gallons withdrawn (thousands)	Standard plate count at 35°C (number/ml)	Coliform confirmed (MPN [1]/100 ml)
6-2	2	>300	>240
	6	>300	>240
	24	>300	>240
	86	>300	>240
6-3	576	>300	>240
	883	44	240
6-4	1,483	<30	240
	1,699	<30	240
6-5	2,299	<30	38
6-23	7,207	>300	>240
	7,327	<30	38
6-27	10,580	<30	5
7-1	10,586	>300	>240
	10,676	<30	8.8
7-15	10,682	>300	>240
	10,778	88	2.2
7-16	11,253	<30	<2.2
8-6	11,346	-----	38
	11,438	-----	<2.2
8-7	11,918	-----	<2.2

[1] Most probable number.

injection stratum, the conductivity represents an average for the water throughout the 60-foot injection zone. For well N7890, conductivity was determined by a down-hole probe throughout most of the test and by pumped samples once per day for the last 3 days of the test. This well is screened roughly in the middle 10 feet of the injection stratum and, hence, the conductivity observed represents more of a point sample than that from well N7886.

The conductivity curves for well N7886 indicate a sharp rise in conductivity once the first change is observed. This suggests that little dispersion of the injected slug is occurring within the first 20 feet of travel. The curves for well N7890 indicate a more gradual rise in conductivity, presumably reflecting a greater amount of dispersion of the water-quality front as it moves out greater distances from the injection well. Permeability stratification within the injection zone is known to exist, based on geologic observation of core samples and on current-meter observations of flow within the screened part of the well (G. D. Bennett, written commun., 1969). Conductivity profiles in well N7886 suggest that much of the dispersion of the injected slug results from unequal rates of travel of the front through various layers of the injection stratum, as described theoretically by Mercado (1967, p. 23). Diffusion and (or) dilution most likely also account for part of the dispersion observed.

CHANGES IN CHEMICAL QUALITY

In gross aspect, little change occurred in the chemistry of the injected water as it moved through the aquifer, based on present information. In detail, however, some noteworthy changes were observed. The chemical character of the injected water and of water from observation wells N7886 and N7890 is depicted diagrammatically in figure 6. Comparison of the characterization of the injection water with that from N7886 for tests RW4 and RW5 indicates that calcium and bicarbonate are the only major constituents to show much change; both decrease with movement through the aquifer. According to F. J. Pearson, Jr. (written commun., 1969), the most likely cause for this decrease is the exchange of calcium for hydrogen, in addition to other cations, on the clay minerals contained in the Magothy aquifer. The liberated hydrogen ions would react with bicarbonate in solution to produce nonionized H_2CO_3, which does not appear in the

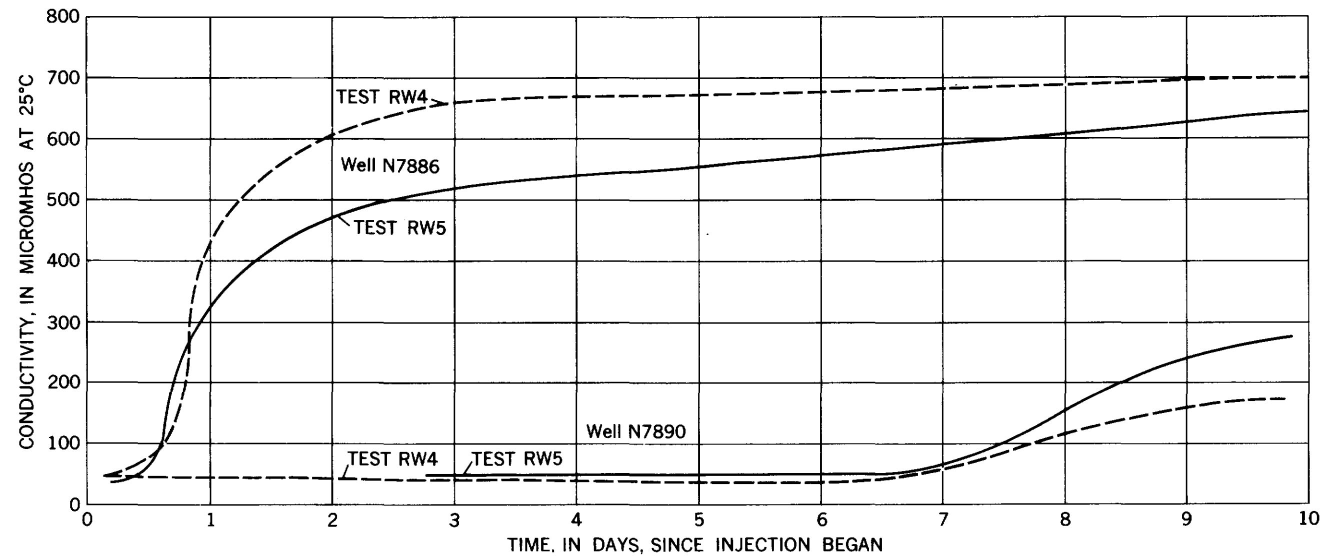

FIGURE 5.—Conductivity of water from observation wells N7886 and N7890 during injection tests RW4 and RW5.

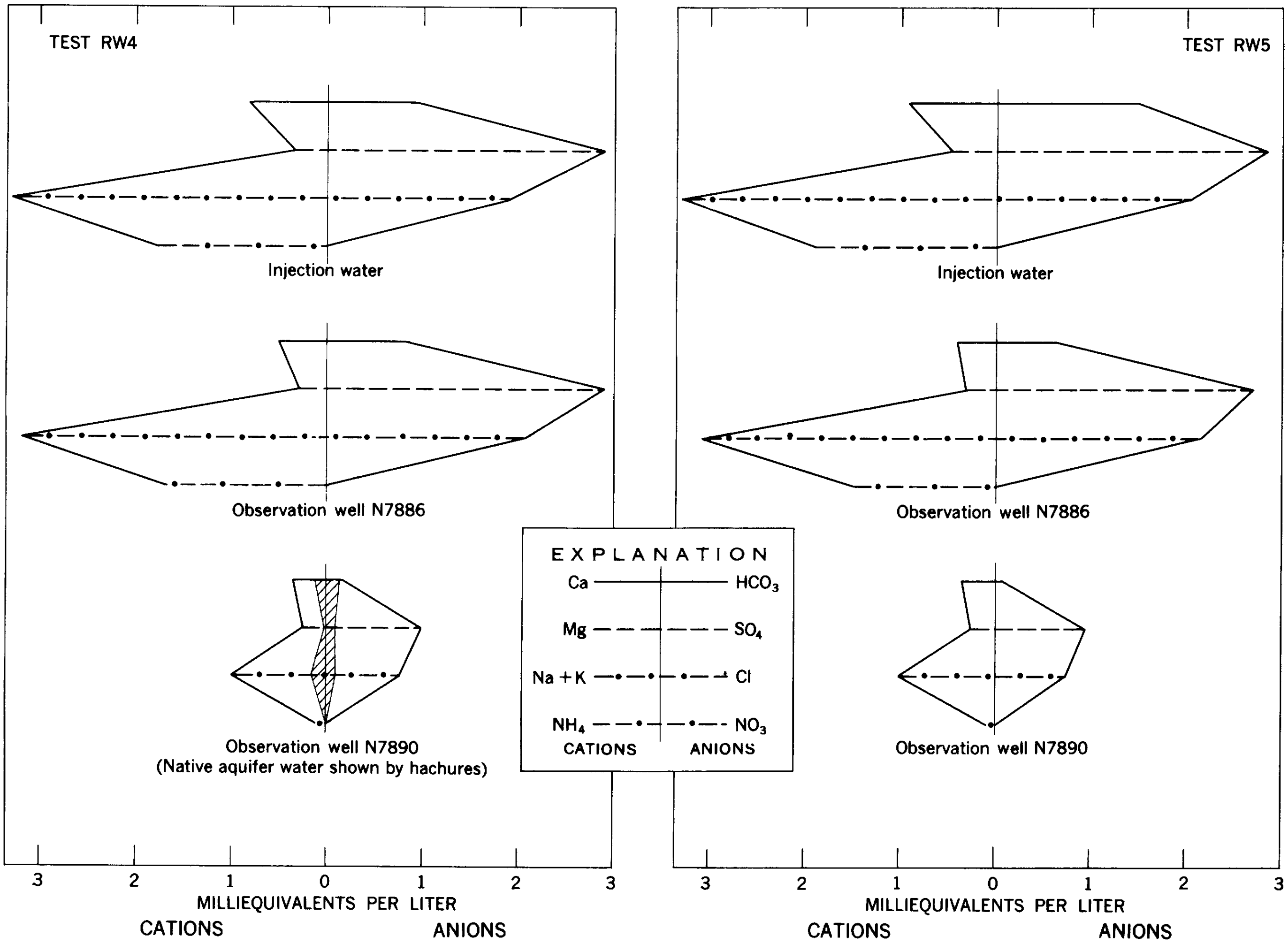

FIGURE 6.—Diagrammatic representation of the chemistry of the water injected (median) in tests RW4 and RW5 and that recovered after 10 days of injection from observations wells N7886 and N7890.

analysis, and therefore, results in an apparent loss of bicarbonate ion. Table 8 lists more complete analyses of water obtained from the observation wells.

In conjunction with the reduction in calcium and bicarbonate content, the water from well N7886 showed a decrease in total and calcium hardness, alkalinity, and pH, and an increase in carbon dioxide. Other noteworthy changes include a large loss in phosphate content, which presumably reflected a concentration of phosphate around the injection well. Iron content increased considerably, most likely as a result of dissolution of pyrite and (or) other iron-bearing minerals contained within the injection stratum. Dissolved-solids content of the water was about 10 percent less than that of the injected water, but, with continued injection and more complete flushing of native aquifer water, together with the establishment of a new equilibrium between the injected water and the aquifer framework, the dissolved-solids content of the water from well N7886 may approach that of the injected water.

The chemical character of the water from well N7890, as shown in figure 6 and table 8, indicates that this water was a mixture of aquifer water and injection water even after 10 days of injection. The iron content, as in water from well N7886, was considerably higher than both the injected water and the native aquifer water.

MIGRATION OF COLIFORM BACTERIA

Although the water injected is relatively free of coliform bacteria, a proliferation of coliform bacteria has been noted in the immediate area of the injection well upon cessation of injection. Sparse evidence thus far suggests that coliform bacteria may be migrating through the aquifer along with the injected water, at least as far as well N7886, 20 feet away from the injection well. Movement of bacteria is slower than that of

TABLE 8.—*Selected chemical-quality characteristics of water recovered after 10 days of injection from observation wells N7886 and N7890*

[All constituents in milligrams per liter except pH. Analyses by Nassau County Department of Health, except for SiO_2, Ca, Mg, Na and K which were made by U.S. Geological Survey. MBAS, methylene blue active substances]

	N7886		N7890	
Test No.	RW4	RW5	RW4	RW5
Total iron	0.58	0.91	0.64	1.30
Free CO_2	80	105	55	100
Fluoride	.29	.23	.18	<.10
Ammonia nitrogen	25	18.5	1.30	1.38
Albuminoid nitrogen	.36	.24	.018	.04
Nitrite nitrogen	<.001	<.001	<.001	<.001
Nitrate nitrogen	<.05	<.05	<.05	<.05
Oxygen consumed	1.8	2	.9	1
Chloride	67	74	28	24
Total hardness	44	42	44	34
Total alkalinity	41	33	7	6
pH	6	5.8	5.4	5.1
Total solids	342	321	120	123
MBAS	<.02	<.02	<.02	<.02
Calcium hardness	26	22	40	16
Total phosphate	.14	.60	.02	.02
Orthophosphate	.13	.50	.02	<.01
Sulfate	132	138	60	54
Silica	12	10	8.2	8.0
Calcium	10	8.2	7.8	7.2
Magnesium	3.5	4.2	3.1	3.3
Sodium	67	67	23	22
Potassium	10	9	2	1.6

the water itself, perhaps because of the time necessary for regrowth around the injection well. However, much more study is necessary to define the rate and distance of migration.

SUMMARY OF PRELIMINARY CONCLUSIONS

Recharge with highly treated sewage-plant effluent has been conducted intermittently at Bay Park since October 1968. Preliminary findings to date are:

1. Head buildup in the injection well (but not the aquifer) in each test thus far has exceeded that predicted by pumping-test data, even though the water injected was of potable quality. In one test, the specific capacity of the injection well was reduced to about 50 percent of the preinjection value after 10 days of injection.
2. The amount of excessive head buildup in the injection well was strongly dependent upon the turbidity of the recharge water, even though turbidity levels were less than a few milligrams per liter as SiO_2. A small increase in suspended matter had an appreciable effect on the excessive head buildup.
3. Most of the particulate matter injected was filtered out and retained at or near the aquifer-gravel pack interface.
4. Degasification of the injection water has not resulted in a measurable reduction of clogging of the injection well.
5. Specific capacity of the injection well, which was reduced during injection, was largely restored by pumping.
6. Water recovered from the injection well after each test initially was very turbid and contained high concentrations of iron, phosphate, and volatile suspended solids. It was also high in bacterial content.
7. Little change occurred in the chemistry of the injected water as it moved through the aquifer for distances of 20 feet. Changes noted include a decrease in calcium and bicarbonate content, and conjunctively, a decrease in hardness, alkalinity, and pH. Phosphate content also decreased, but iron content increased.

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