

SINGLE-WELL INJECTION AND RECOVERY OF FRESHWATER FROM AN AQUIFER CONTAINING SALINE WATER AT ARECIBO, PUERTO RICO

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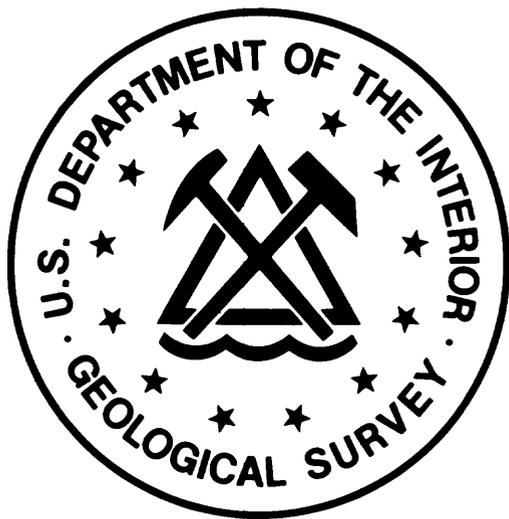
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CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for inch-pound units used in this report are listed below:

<u>Multiply</u>	<u>By</u>	<u>To obtain metric unit</u>
<u>Length</u>		
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
<u>Area</u>		
square foot per day (ft ² /d)	0.09294	square meter per day (m ² /d)
square mile (mi ²)	2.590	square kilometer (km ²)
<u>Volume</u>		
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m ³)
million gallons (Mgal)	3,785	cubic meter (m ³)
<u>Flow</u>		
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic feet per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
gallon per minute per foot (gal/min/ft)	0.2070	liter per second per meter (L/s/m)
<u>Pressure</u>		
pound per square foot (lb/ft ²)	4.88	kilogram per square meter (Kg/m ²)
<u>Density</u>		
pound per cubic foot (lb/ft ³)	16.02	kilogram per cubic meter (Kg/m ³)
<u>Temperature</u>		
degree Fahrenheit (°F)	5/9(°F-32)	degree Celsius (°C)



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ABSTRACT

The feasibility of injecting, storing, and recovering excess streamflow in a saline aquifer was investigated for a well site in the lower Río Grande de Arecibo valley, at Arecibo, Puerto Rico. Six injection-recovery tests were made, which included various injected volumes and storage periods. Injected volumes ranged from 0.6 to 6.6 million gallons. The storage period ranged from 6 minutes to nearly 31 days. Chloride-load accounting was used to indirectly measure the volumes of injected water recovered. Injected water recovered during the tests ranged from 0.12 to 2.1 million gallons (21 and 32 percent, respectively, of total volumes injected). Graphical projections were used to predict the maximum recovery efficiency for various combinations of injected volumes and storage periods. Predicted maximum recovery efficiency generally was less than 60 percent. The specific capacity of the test well was decreased about 25 percent as a consequence of injecting water that had a relatively large concentration of suspended sediment (about 100 milligrams per liter). Calculations of chemical equilibrium were made to determine if chemical reactions would occur between the injection water and minerals commonly found in limestones. These calculations indicate that the injected water was supersaturated with calcite, and the aquifer water may be supersaturated with calcite, dolomite, aragonite, and magnesite; this presents a possibility for mineral precipitation.

INTRODUCTION

Background

North-central Puerto Rico (fig. 1) has been subjected to extensive water-resources development as a consequence of the implementation of a rice-growing industry coupled with the continuous growth of the chemical and pharmaceutical industries. The principal rivers (Río Grande de Arecibo, Río Grande de Manatí, and Río Cibuco) of the north-central area can provide more than 150,000 acre-ft/yr (acre-feet per year) of potable water. The major aquifers of Puerto Rico, which are located in this area, provide

about 60,000 acre-ft/yr for industrial, public, and agricultural supplies. A water-resources development plan (Santiago-Vázquez, Flaherty, and Giavara, 1982) indicated that about 180,000 acre-ft/yr of combined surface water and ground water would be required from this area to provide future public-water supply for the rapidly growing San Juan metropolitan area. Recent water-resources investigations have indicated that saltwater is migrating inland as a consequence of increasing ground-water withdrawals (Torres-González and Díaz, 1984; Gómez-Gómez, 1984; Quiñones-Aponte, 1986).

Artificial recharge would be helpful in increasing aquifer storage and in controlling the inland migration of saline water. Artificial recharge is a means of augmenting the infiltration of surface water into a ground-water system at a rate that vastly exceeds that which would occur naturally (Pettyjohn, 1981, p. 3). The U.S. Geological Survey, in cooperation with the Puerto Rico Department of Agriculture, began a study in 1984 to test the feasibility of artificial recharge to aquifers containing saline water.

Purpose and Scope

The purpose of this study was to test the feasibility of injecting excess streamflow into aquifers containing saline water in order to store water for use when surface-water resources are minimal and to prevent the inland migration of saline water.

This report presents the results of a pilot study that used a single injection-recovery well, rather than the more conventional artificial recharge methodologies such as injection well fields and surface spreading. The well selected was the Monte Grande well at Arecibo (fig. 1), where existing facilities were adequate for the injection-recovery experiment. The Monte Grande well was abandoned after the aquifer was subjected to widespread saltwater encroachment caused by extensive ground-water withdrawals. Nearby wells were also affected by saltwater encroachment.

The study presents an empirical approach in analyzing the chloride data sets to indirectly deter-

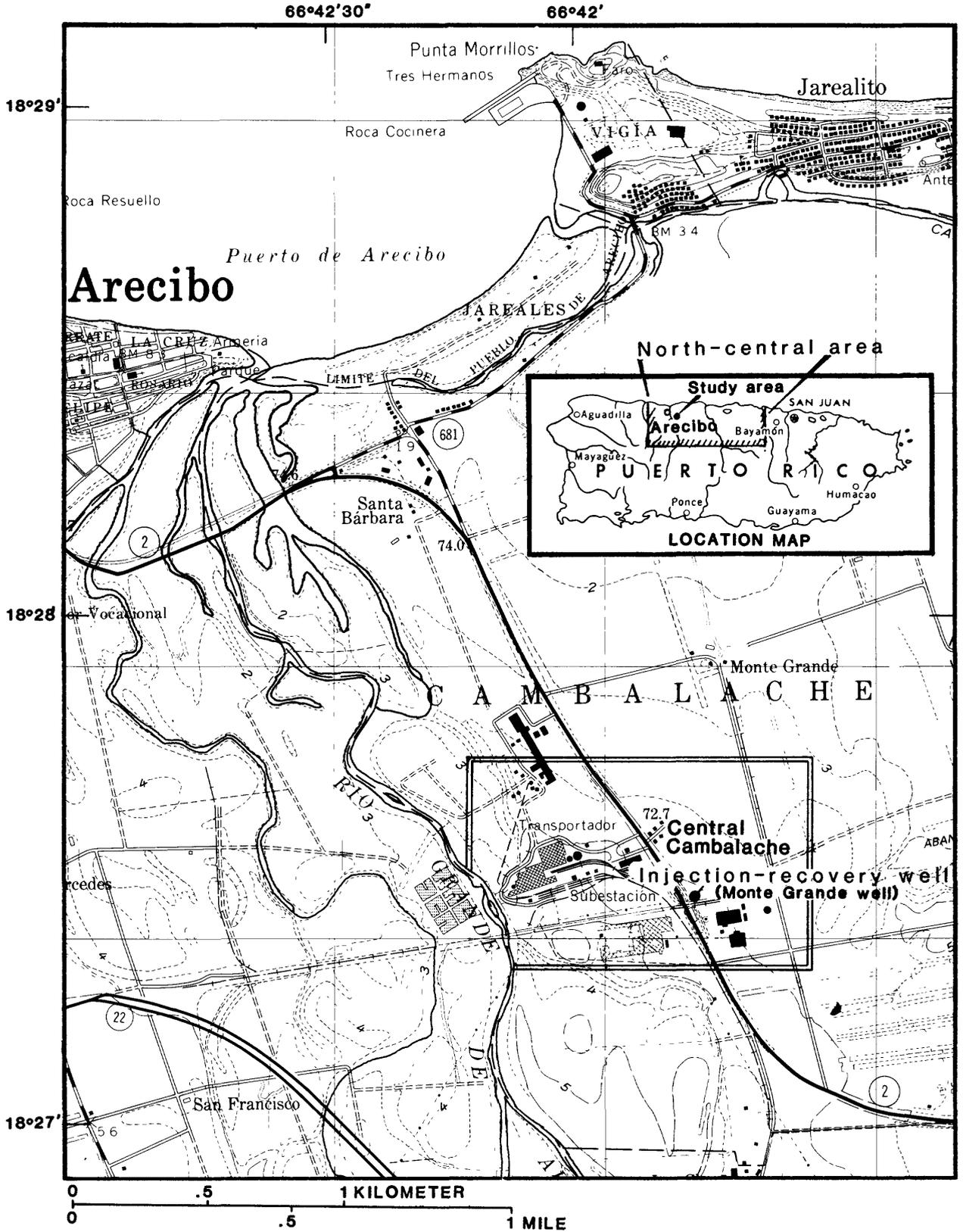


Figure 1.--Location of the Injection-recovery well near Arecibo, Puerto Rico.

mine the volume of water recovered because an analytical approach would have been inappropriate or impractical. Information regarding the hydrogeology and geochemistry of the aquifer at the test site was minimal, and there were no observation wells available to collect hydrologic information. The study was limited to measuring water-quality changes, accounting for the volumes injected and recovered, and defining some hydraulic characteristics of the well-aquifer system.

HYDROLOGIC CONDITIONS

Source of Injected Water

The streamflow regime in Puerto Rico provides an ideal source of water for artificial recharge of the aquifers. Streamflow responds to a period of intense rainfall, usually during May through June, and a wet season from August to December. During these periods, most of the water from streams flows to the Atlantic Ocean before it can be intercepted for any public supplies, irrigation, or industrial use.

Río Grande de Arecibo flows one half mile west of the injection-recovery well (fig. 1). It has a mean annual discharge of 527 ft³/s (cubic feet per second) or 382,000 acre-ft/yr, at Central Cambalache gaging station. Río Grande de Arecibo has the largest discharge in Puerto Rico. The lowest mean daily discharge of Río Grande de Arecibo during 1969-82 was 50 ft³/s. The flow of Río Grande de Arecibo is controlled by a dam that forms Dos Bocas Reservoir which is used to operate a hydroelectric plant. Water released daily

from Dos Bocas Reservoir amounts to about 12,000,000 ft³ or 275 acre-ft (Quiñones-Aponte, 1986, p. 15). The water flows through the valley and discharges to the Atlantic Ocean. This release, plus the natural flow of Río Grande de Arecibo, provides a reliable source of water for injection.

Aquifer and Injection-Well Characteristics

The hydraulic gradient of the alluvial-Ayamamón aquifer at the Monte Grande well site is nearly flat at about 0.0008 ft/ft (foot per foot) (Giusti, 1976). The apparent transmissivity of the aquifer ranges from 55,000 to 80,000 ft²/d (feet squared per day) (Whitesides and others, 1985). The flat hydraulic gradient and relatively high aquifer transmissivity optimize the possibility for successful acceptance of injected freshwater to, storage within, and recovery from the aquifer containing saline water. A detailed description of the aquifer characteristics in the Arecibo valley area is given by Quiñones-Aponte (1986).

The Monte Grande well is from 12 to 16 inches in diameter and about 150 ft deep. It is cased with slotted-steel pipe from the surface to about 100 ft through a predominantly clayey alluvium. The remaining 50 ft are open to the Ayamamón Limestone of Miocene age (fig. 2). Results of a fluid resistivity log (fig. 2) show that the water is more saline in the lower 50 ft (where the Ayamamón Limestone occurs), and almost fresh in the upper 40 ft where a perched condition occurs. From 50 to 100 ft, the water increases in salinity. The composite water level in the

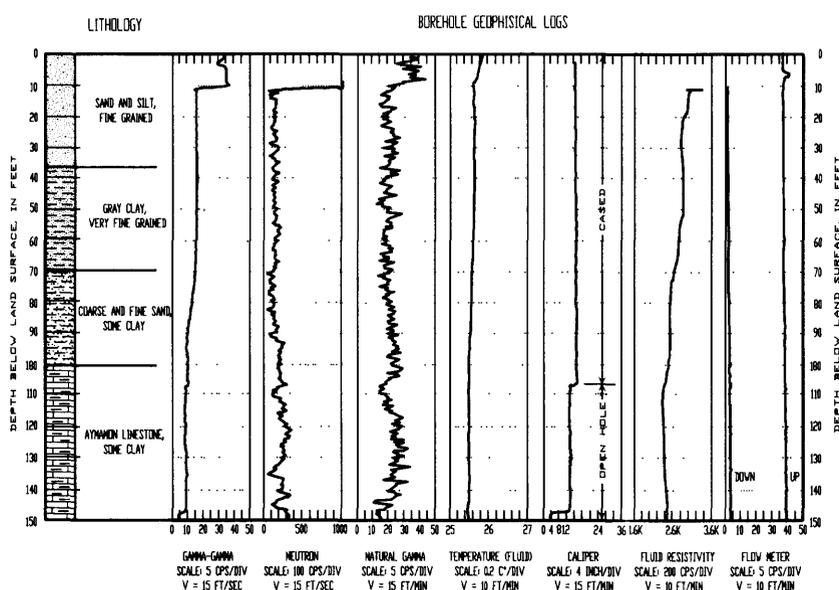


Figure 2.--Lithology and borehole geophysical logs of the Monte Grande well.

well is approximately 10 ft below the land surface.

Borehole geophysical logs were run in the Monte Grande well to determine physical and chemical properties of the well-aquifer system (fig. 2). The gamma-gamma and neutron logs reveal that the Aymamón zone (100 to 150 ft) is more dense and less porous than the alluvium (0 to 100 ft), but may have a greater secondary porosity owing to solution openings. These solution openings imply that inland migration of saline water may be advancing more rapidly within the Aymamón Limestone than through the alluvial deposits (fig. 2).

INJECTION-RECOVERY ASSESSMENT

The recovery efficiency is a measure of the success of a cycle of injection, storage, and recovery (Merritt and others, 1983, p. 2). Usually expressed as a percentage of the volume injected, recovery efficiency is defined as the volume of water recovered before the mixed water withdrawn fails to meet some established water-quality standard. Limits of 2,000 $\mu\text{S}/\text{cm}$ (microsiemens per centimeter at 25° Celsius) of specific conductance and 500 mg/L (milligrams per liter) of chloride concentration were used to define usable water withdrawn from the Monte Grande well. Most crops, including rice, will normally not tolerate higher levels of chloride concentration.

The water from the Río Grande de Arecibo, used for artificially recharging the aquifer, ranges in specific conductance from 220 to 350 $\mu\text{S}/\text{cm}$. The chloride concentration ranges from 9 to 14 mg/L. In contrast, the water from the alluvium-Aymamón aquifer in the vicinity of the well has a specific conductance of about 3,180 $\mu\text{S}/\text{cm}$ and a chloride con-

centration of 970 mg/L.

Injection-Recovery Procedures

Freshwater was injected into the aquifer through the Monte Grande well. The well head is adjacent to and about 2 feet lower than a section of a concrete culvert and control box that conveyed water from Río Grande de Arecibo to the nearby rice plantations (fig. 3). An 8-inch steel pipe with a 50-slot galvanized well screen was installed within the culvert to prevent water-borne debris and animals from entering the well. Water from the culvert entered the screen and steel pipe and flowed by gravity into the well when the level in the control box was elevated by a downstream control. A gate valve controlled the flow into the well (fig. 3).

The injection-recovery test proceeded as follows: prior to each test, the well was pumped at a discharge of 380 gal/min (gallons per minute) to withdraw a small amount of accumulated water that had cascaded into the well from the fresher water aquifer in the upper part of the alluvium (fig. 2). These tests were run until equilibrium was achieved with respect to specific conductance, indicating that aquifer water was being discharged from the well. Injection of surface water to the aquifer then proceeded by gravity flow. Recovery began after a designated storage period (table 1), and continued until the chloride concentration of the pumped water was at or near the pre-injection concentration (aquifer water). Six tests were run during the study (table 1). Average-injection flow rates ranged from 300 to 456 gal/min. Pumping rates for recovery of the injected water were generally about 380 gal/min, except for test 1, when the pumping rate was 300 gal/min.

Table 1. Summary of results from chloride-load injection-recovery tests.

Test number	Total water injected (V_i) (gallons)	Injected* water recovered (V_r) (gallons)	Storage period (S_p) (minutes)	Injection time (I_t) (minutes)	Pumping time (P_t) (minutes)	** Q_r (gallons per minute)	Maximum recovery efficiency, (V_r/V_i) (in percent)
1	600,000	283,300	6	1,350	3,500	81	47.20
2	600,000	192,664	4,146	1,380	2,600	74	31.10
3	600,000	125,692	12,741	1,380	2,050	61	20.95
4	6,600,000	2,095,343	6	14,478	9,900	211	31.75
5	4,300,000	1,058,197	20,400	14,280	8,800	180	21.92
6	5,860,000	1,231,000	44,550	14,160	8,100	152	21.00

* Equation 7

** $Q_r = V_r/P_t$

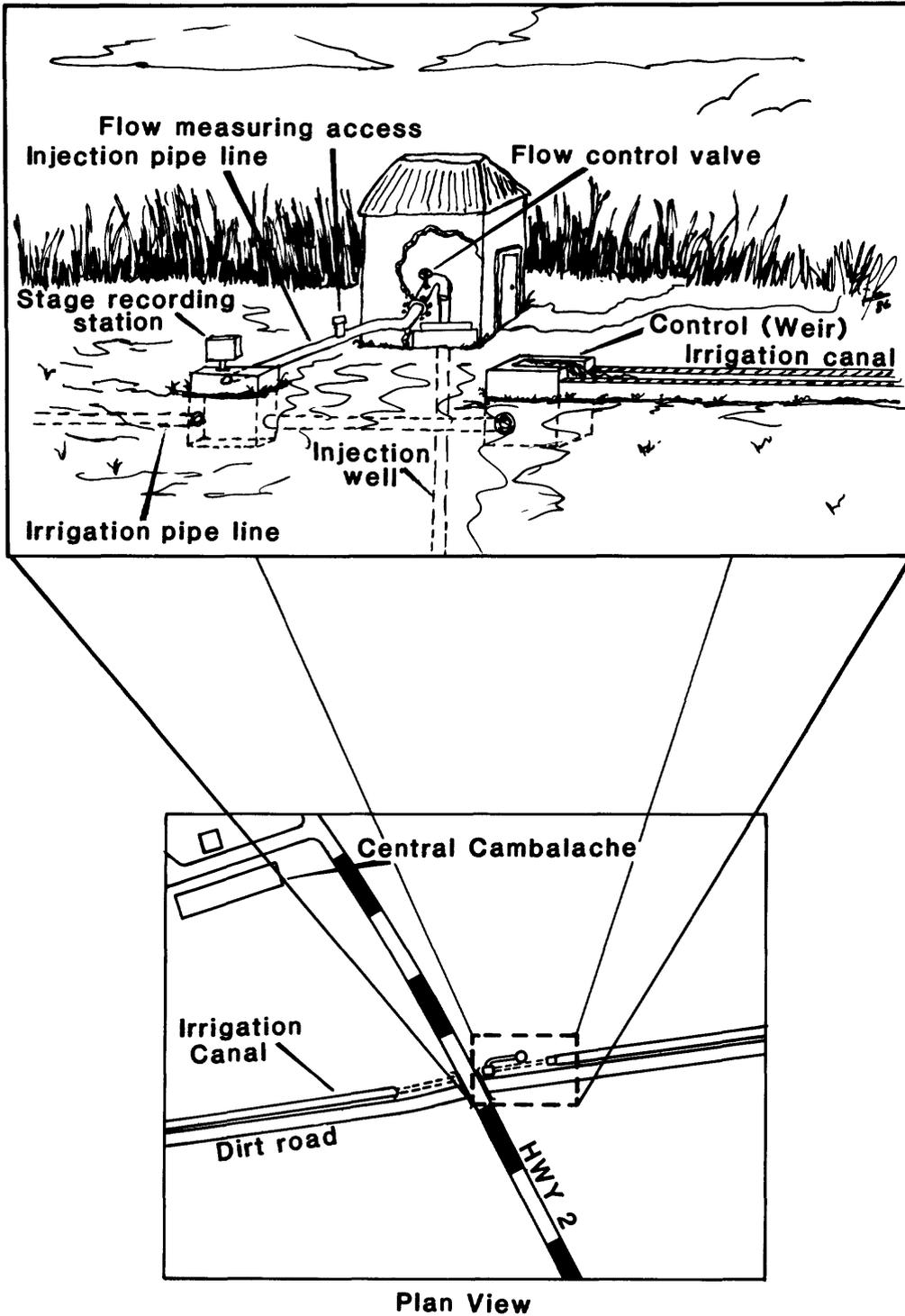


Figure 3.--Schematic location and details of the injection-recovery well facilities near Arcibo.

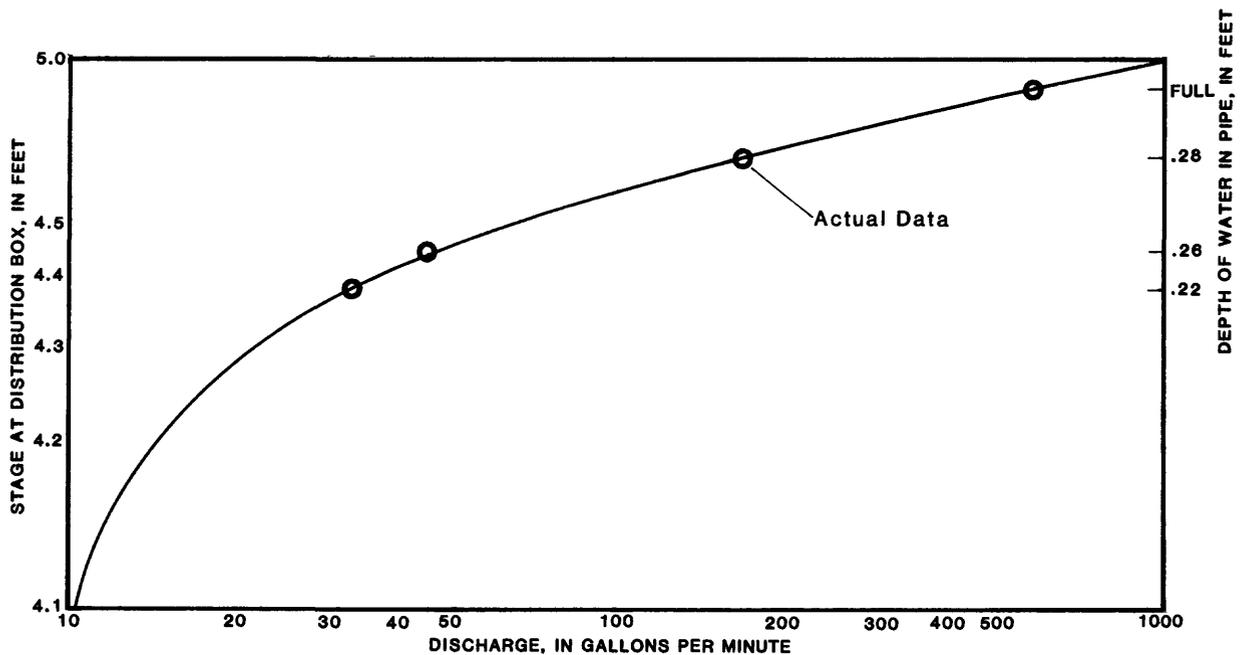


Figure 4.--Stage-discharge relation for the injection pipe line.

Specific conductance was recorded hourly during both the injection and recovery parts of each test. Water samples were collected periodically at the pump outlet for laboratory determination of chloride concentration.

Analyses of Injection-Recovery Data

The volume of injected water was determined by using standard Survey procedures described by Kennedy (1983). A stage-discharge relation (fig. 4) was prepared for the stage recording station (fig. 3) and discharges through the injection pipe line. The recorded stages (fig. 5) were translated into discharge values and the injected volume computed by integrating the varying discharge rates with respect to the injection time (table 1).

The water withdrawn during the recovery part of the test can be classified according to two criteria: the usable mixed volume of aquifer water plus injected water, and the maximum recoverable portion of the injected water. The usable mix represents the mixed volume of aquifer water and injected water pumped out when an arbitrarily preselected water-quality limit is reached (fig. 6). The volume of usable mix is determined by multiplying the time at which the desired water-quality limit is reached by the recovery pumping rate.

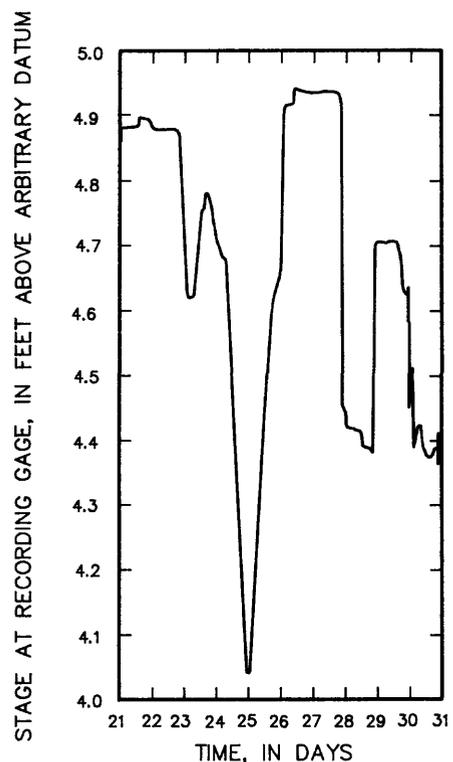


Figure 5.--Stage recorded at the distribution box during injection test 5.

The maximum recoverable portion of the injected water or "maximum injected water recovered" is defined as the total amount of injected water that can be retrieved through an injection-recovery well, if pumping continues for an infinite amount of time. For practical purposes, a time limit is established beyond which the proportion of freshwater in the mix is insignificant.

A chloride-load accounting approach was used to determine indirectly the maximum amount of recoverable injected water (table 1).

The chloride load (CL) at any time was determined by equation (1):

$$CL = Q \times CC \times [3.785 \times 10^{-3}], \quad (1)$$

where:

CL = chloride load, in grams per minute;

Q = pumping rate for injection or recovery, in gallons per minute;

CC = chloride concentration, in milligrams per liter; and

3.785×10^{-3} = conversion factor from milligrams and gallons to grams and liters respectively.

The chloride-load approach consisted of the following steps: (1) Determine the chloride loads (CL) at different time intervals during the recovery pumping; (2) establish the upper and lower limits of CL; and (3) integration to estimate volume recovered.

The upper limit (UL) of CL is determined by the asymptote of the CL-time curve (fig. 6), which varies as the pumping rate for recovery changes. The lower limit (LL) (CL of the injected water) can be considered constant if the injection rate and the chloride concentration of the injected water does not change.

Integration of the area above the CL-time curve was performed by defining the instantaneous CL(t) as a function of time:

$$CL(t) = \frac{(Q_r(t) LL + Q_n(t) UL)}{(Q_r(t) + Q_n(t))}, \quad (2)$$

where:

$Q_r(t)$ = injected component of pumped water, and

$Q_n(t)$ = aquifer component of pumped water.

The total pumping rate ($Q_p(t)$) is then given by:

$$Q_p(t) = Q_r(t) + Q_n(t). \quad (3)$$

Combining (2) and (3) and rearranging yields,

$$Q_r(t) = Q_p(t) \frac{UL - CL(t)}{UL - LL}. \quad (4)$$

Then the total amount of injected water recovered (V_r) is:

$$\begin{aligned} V_r &= \int_0^{\infty} Q_r(t) dt, \\ &= \frac{1}{UL - LL} \int_0^{\infty} Q_p(t) (UL - CL(t)) dt, \end{aligned} \quad (5)$$

and for a constant pumping rate (Q_p):

$$V_r = \frac{Q_p}{UL - LL} \int_0^{\infty} (UL - CL(t)) dt. \quad (6)$$

The volume of injected water recovered (V_r) can be approximated by integrating the term (UL - CL(t)) with respect to time and multiplying by the constant pumping rate (Q_p) divided by the difference between the upper and lower limits (UL - LL), until the asymptote of the CL-time curve is reached. This can be expressed as:

$$\begin{aligned} V_r &= \frac{Q_p}{UL - LL} \sum_{t=t_0}^{Lt} [(UL - \bar{CL}_1)(t_1 - t_0) + \dots \\ &\dots (UL - \bar{CL}_2)(t_2 - t_1) + (UL - \bar{CL}_i)(t_i - t_{i-1}) + \dots \\ &\dots (UL - \bar{CL}_L)(Lt - t_i)], \end{aligned} \quad (7)$$

where:

Lt = time when the asymptote of the CL-time curve is reached, and

$$\bar{CL}_i = (CL(t_i) + CL(t_{i-1}))/2.$$

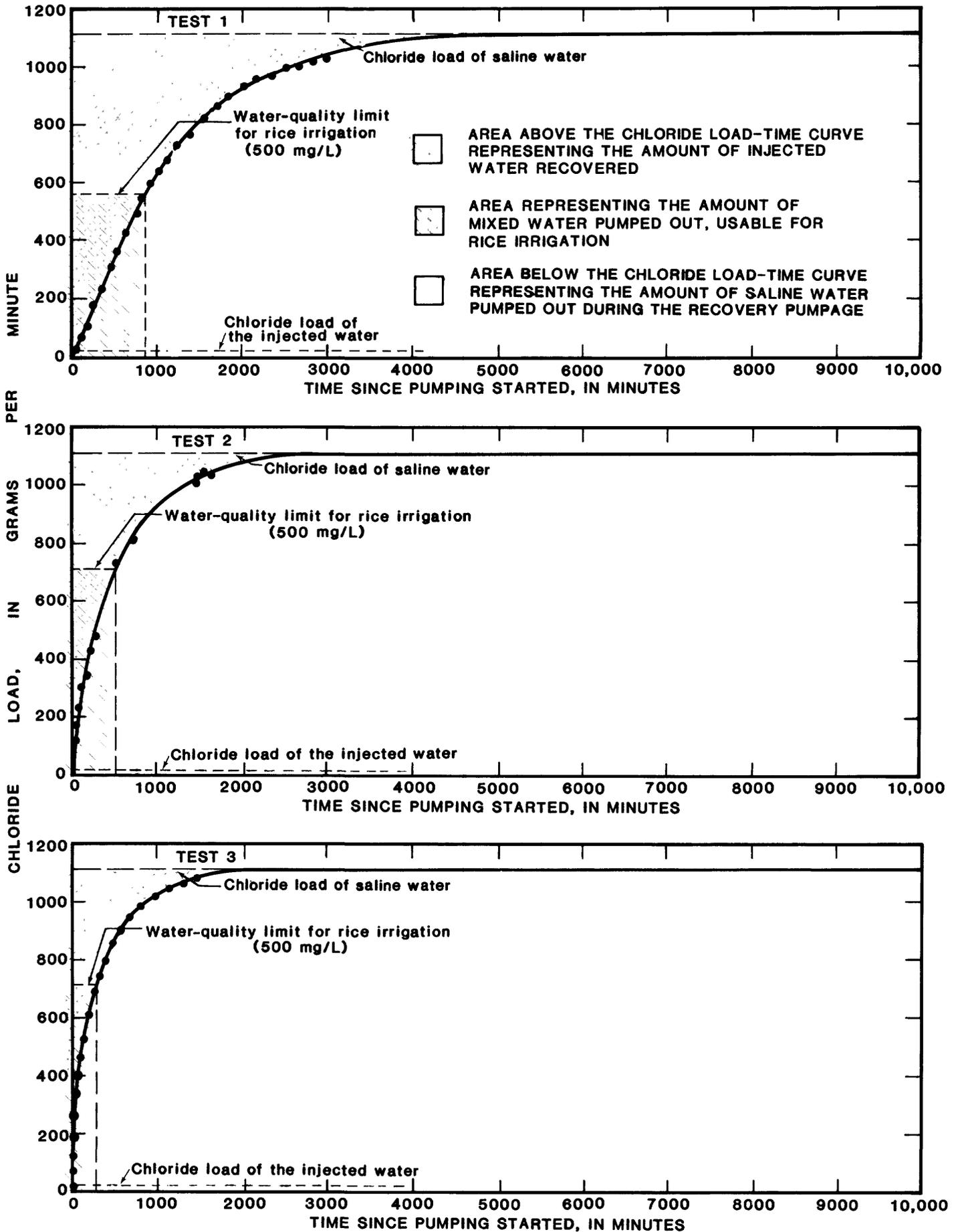


Figure 6.--Chloride load/time curves and areas representative of freshwater, saline water, mixed water, and water-quality limits.

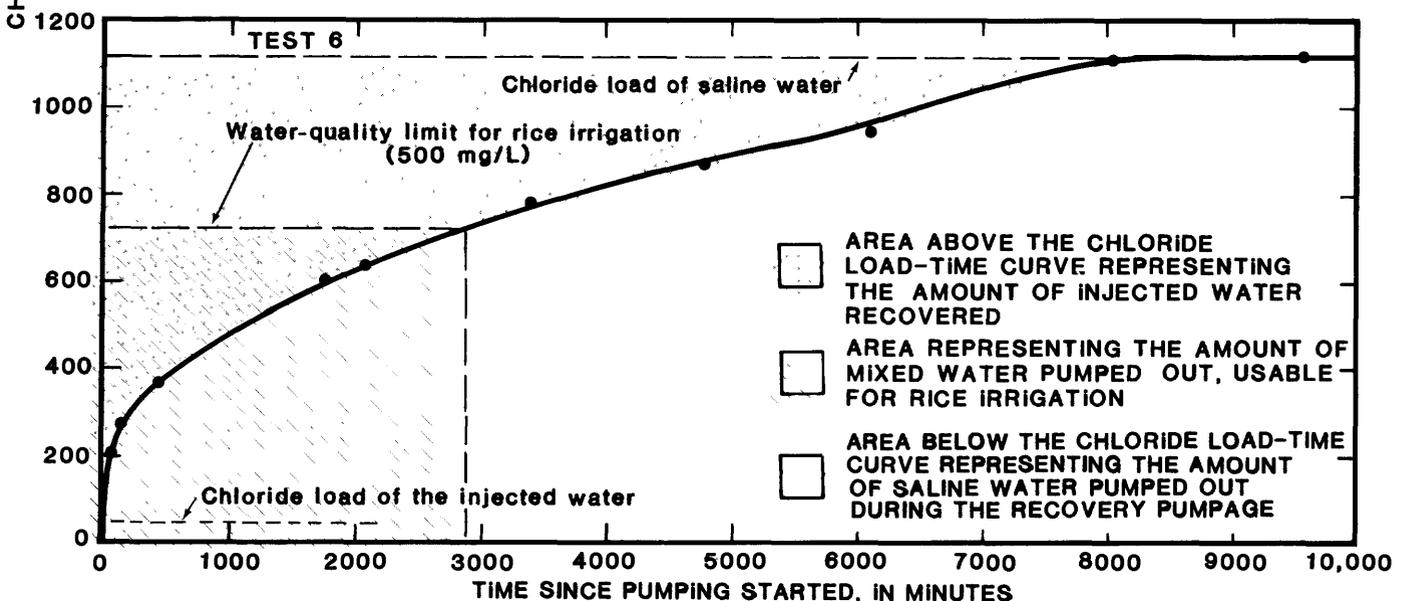
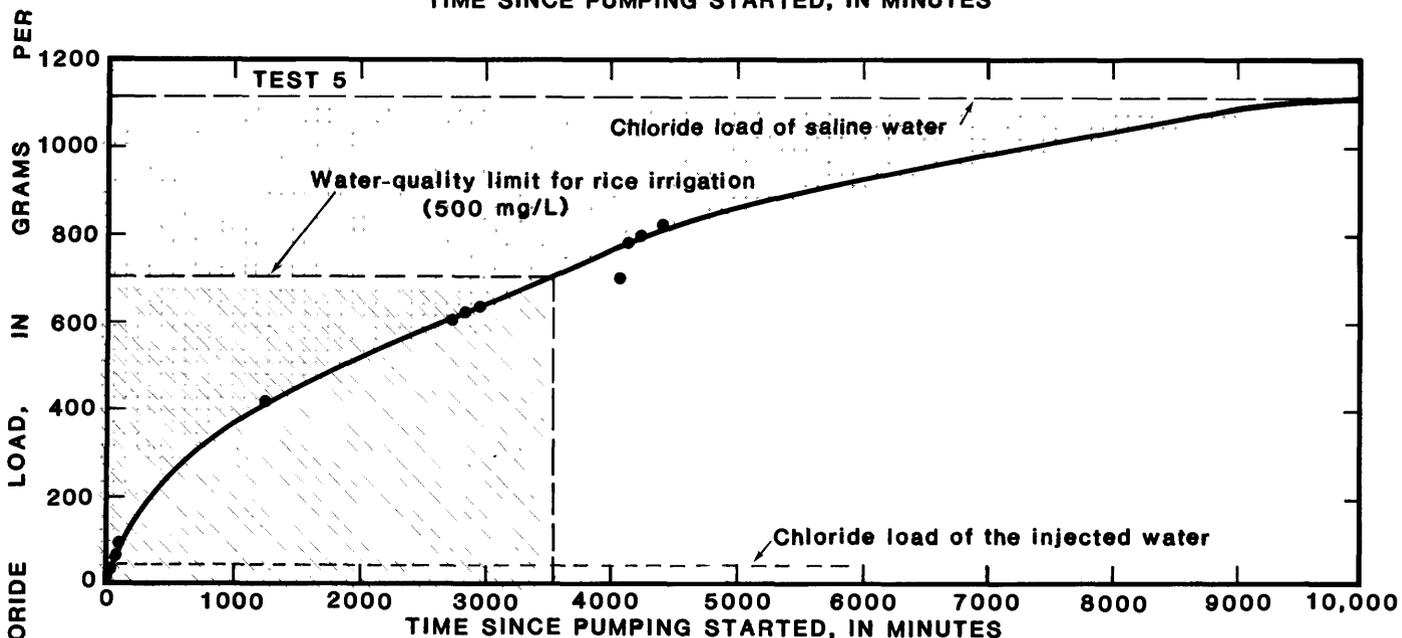
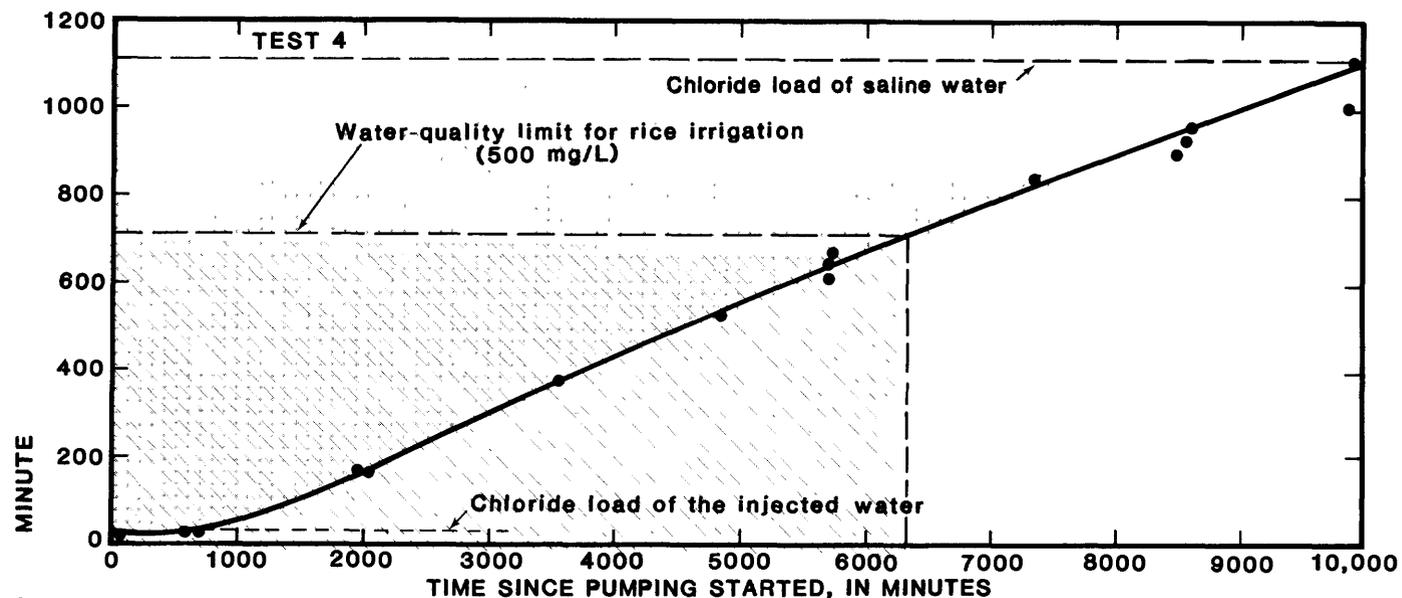


Figure 6.--(Continuation)

Determination of the Recovery Efficiency

The recovery efficiency of the well-aquifer system is a measure of the ability of the system to recover the injected water, and is defined as a percentage of the injected water. The recovery efficiency obtained when the mixed water reaches pre-established water-quality limits has a more practical application, but the determination of the recovery efficiency in terms of the maximum recoverable portion of the injected water has merit in understanding how much of the injected water is actually lost.

According to Bear and Jacobs (1965), when pumping begins immediately after the recharge period, the maximum recovery efficiency is dependent on the injection time, pumping time for recovery (P_t), and the recovery-pumpage to injection rates (Q_p/Q_i) ratio. If the pumping for recovery begins after an arbitrary storage period (S_p), the duration of the storage period also affects the recovery efficiency. Graphical

projections were made using the maximum recovery efficiency data points (fig. 7), determined by equation (7). From the analysis of such projections, it can be stated that: (1) The greatest maximum recovery efficiency, probably never exceeding 60 percent, would be achieved for a very small injected volume and the smallest possible storage period; (2) The maximum recovery efficiency for 6-minutes of storage period decreases from 60 to 20 percent as the injected volume increases from 0.01 to 50 million gallons. The efficiency loss can probably be attributed to water that has migrated downgradient, away from the injection site, and is no longer recoverable; (3) For storage periods greater than six minutes, injected volumes ranging from 2 to 4 million gallons seem to optimize the recovery efficiency; and (4) The effect of the storage period on the maximum recovery efficiency decreases as the injected volume increases.

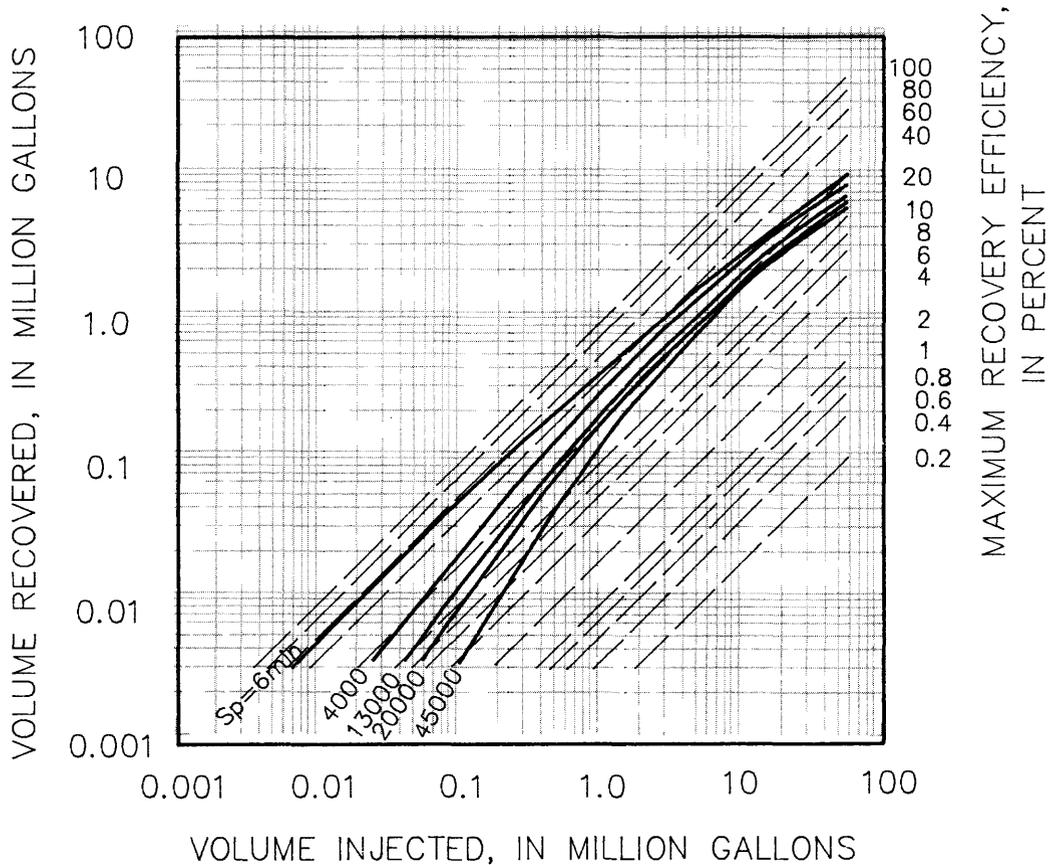


Figure 7.--Graphical projections of the maximum recovery efficiency and maximum volume recovered for different injected volumes and storage periods.

The maximum recovery efficiency could approach 100 percent where aquifer hydraulic gradients are flat. On the other hand, the mixed water recovery efficiency might exceed 100 percent for certain water-quality limits (fig. 8a-f). For example, at a water-quality limit of 600 mg/L of chloride, the recovery efficiency exceeds 100 percent for a storage period of six minutes and small injected volumes (fig. 8e). For a water-quality limit of 750 mg/L, the recovery efficiency exceeds 100 percent for different storage periods for injected volumes ranging from 0.05 to 3 million gallons (fig. 8f). This occurs because the water withdrawn is a mix of the injected and aquifer water and the volume of the mix would be larger than the injected volume.

Interpretations of the graphical projections (fig. 8) for arbitrary selected water-quality limits of 200, 300, 400, 500, 600, and 750 mg/L of chloride, lead to the following conclusions: (1) The mix recovery efficiency increases as the water-quality limit increases; (2) for storage periods approaching zero, the mix recovery efficiency increases as the injected volume decreases; (3) for large storage periods, the mix recovery efficiency for small injected volumes decreases more than for large injected volumes; and (4) for large injected volumes, the maximum recovery efficiency varies within a narrow range, increasing as the storage period decreases. Bear and Jacobs (1965) indicated that the mix recovery efficiency is dependent on the pumping time when the maximum recovery efficiency is achieved, which indicates that the mix recovery efficiency would be related to the maximum recovery efficiency. A graphical correlation was made for the maximum recovery efficiency and mix recovery efficiency for different water-quality limits (fig. 9). From these correlations (fig. 9), it can be inferred that: (1) for small injected volumes and small storage periods, the mix recovery efficiency tends to approach a limit or maximum value at higher water-quality limits; (2) for small injected volumes, the mix recovery efficiency ranges from 0 to 45 percent; (3) for large injected volumes and small storage periods, the maximum recovery efficiency tends to approach a maximum value (over 25 percent in all cases); and (4) for large injected volumes, the mix recovery efficiency ranges widely (between 0 and 100 percent).

WATER QUALITY

The applicability of a particular well for injecting, storing, and retrieving water is dependent on the capability of both the well and aquifer to accept water over a long period of time. Aquifer and well-bore plugging can occur when water of a particular quality

is injected into an aquifer having water of a different quality. Suspended sediments can also be a cause of plugged well-aquifer environments. Additionally, the injected water may promote bacterial growth within the well-aquifer interface; mixing of the injected and aquifer waters could produce chemical reactions that could form mineral precipitates. Those factors can cause a decrease in well efficiency or a reduction in transmissivity in the immediate vicinity of the well bore.

Suspended Sediments in the Injection Water

Suspended sediment concentration in the injection water ranged from 34 to 153 mg/L during the six injection tests. These concentrations are high for water that is to be used for injection purposes. Plugging of the well bore by suspended sediment would be more of a threat where the well is screened in alluvial sediments than in the Aymamón Limestone, which has a high secondary porosity.

The changes in specific capacity of the well and the cumulative suspended sediment injected during the six tests indicated that during test 4, a substantial decrease in the specific capacity occurred (fig. 10). However, during tests 5 and 6, the specific capacity did not decrease, although the amount of sediment injected increased. Initially, the reduction in specific capacity might correspond to the part of the well tapping the alluvium. Further reduction did not occur, probably due to the cavernous nature of the Aymamón Limestone. Cavernous conditions allow the sediment to be disseminated widely, thereby minimizing the chance of a plugged well bore. Removal of suspended sediment should be considered if further studies are to be made.

Chemical Compatibility of Injection and Aquifer Waters

The contrast between the chemical character of the injection and aquifer waters (table 2 and fig. 11) may lead to a chemical reaction (precipitation or dissolution) that could either decrease or increase the specific capacity of the well or aquifer transmissivity near the well. The injection and aquifer waters were classified as calcium bicarbonate ($\text{Ca}(\text{HCO}_3)_2$) and sodium chloride (NaCl) types respectively (fig. 12).

The likelihood for a chemical reaction can be determined by calculating the chemical equilibrium of the injected and aquifer water. The logarithm of the ratio between the ion-activity product (K_{iap}), which can be calculated from the chemical analyses, and the equilibrium value (K_{eg}) for a given mineral would indicate the type of reaction that might take

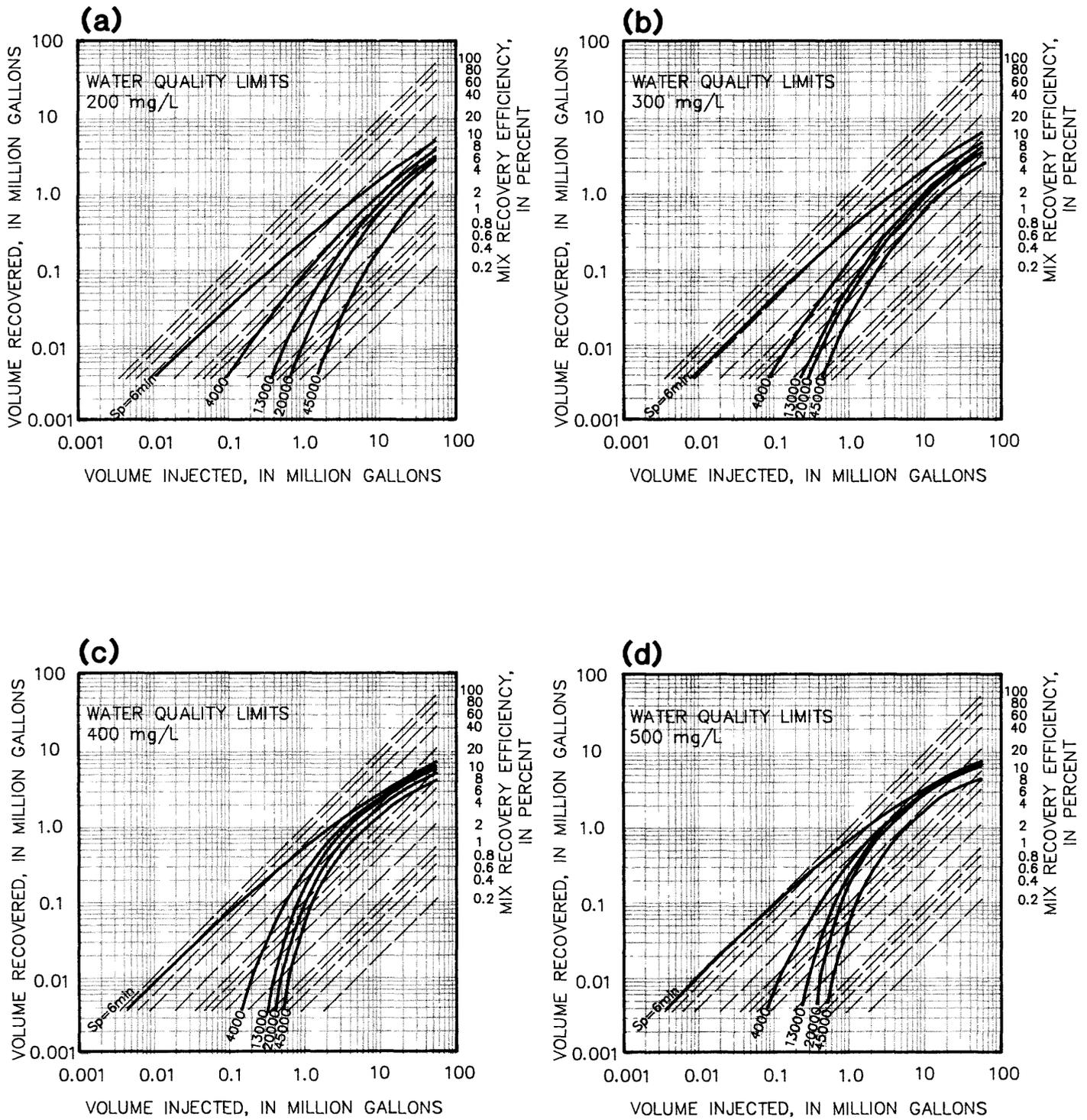


Figure 8.--Graphical projections of the injected and aquifer water recovered for different injected volumes, storage periods, and water-quality limits.

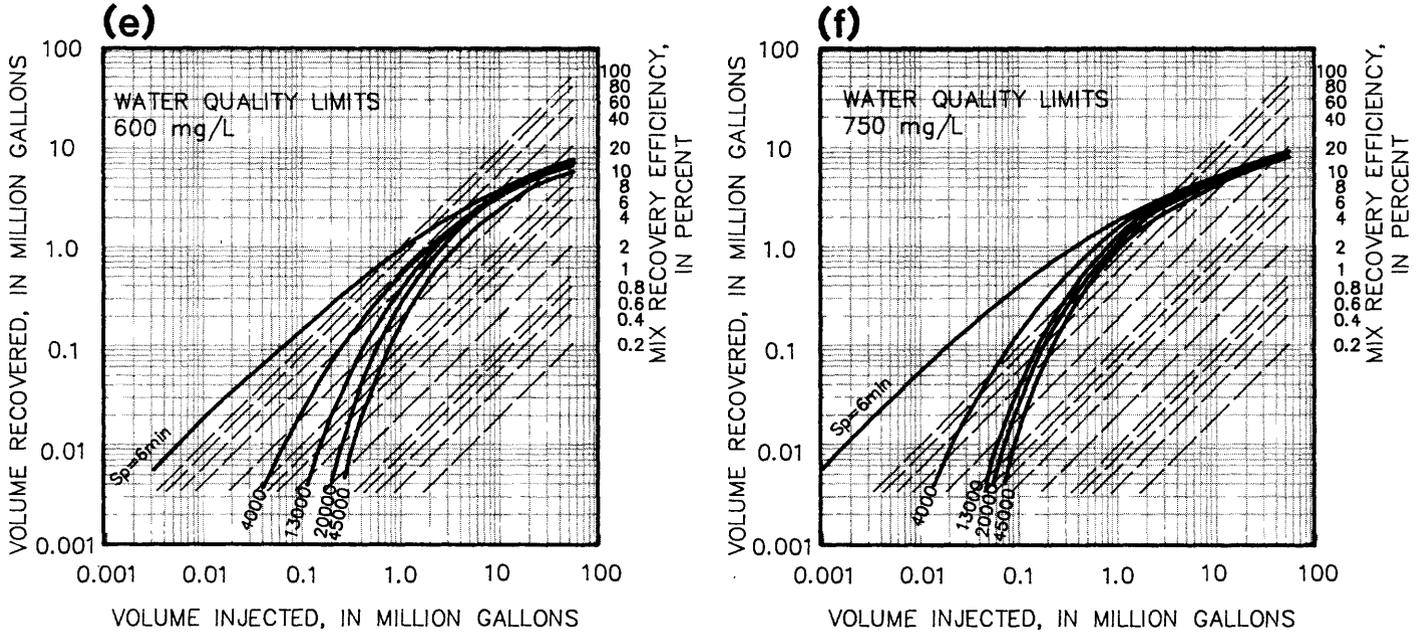


Figure 8.--(Continuation)

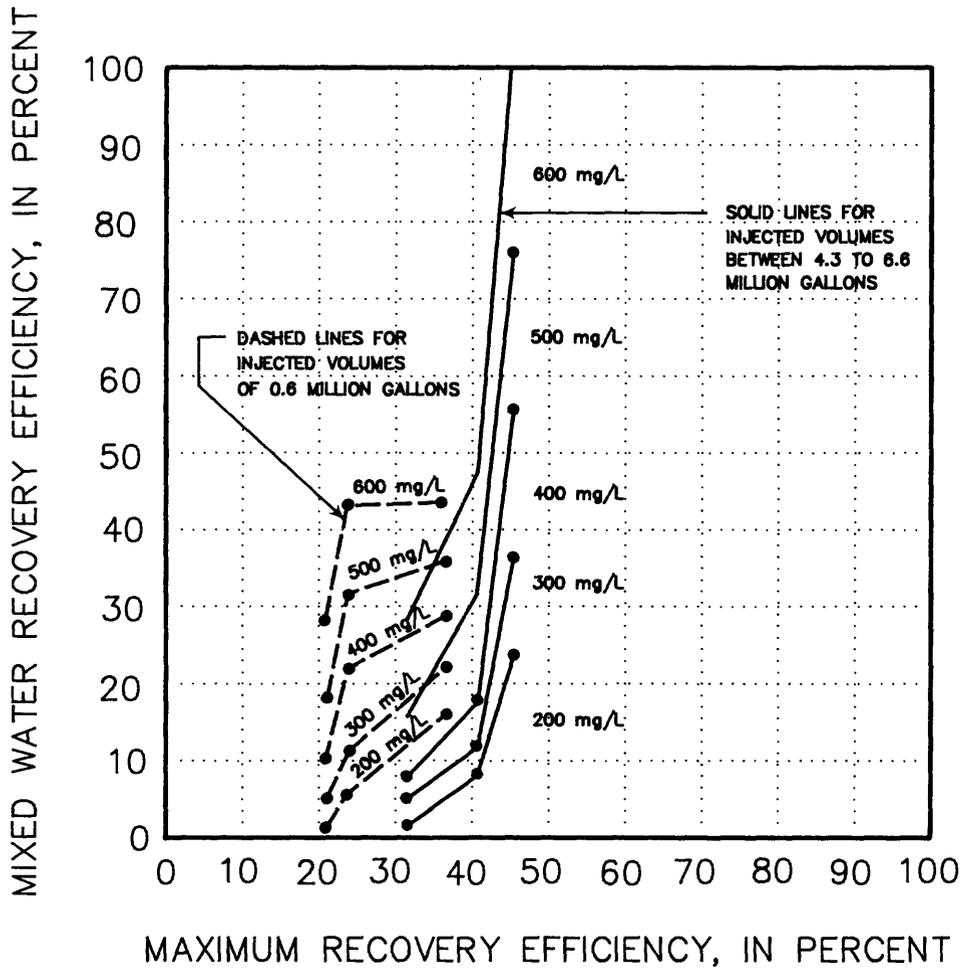


Figure 9.--Relation between the maximum recovery efficiency and the mix recovery efficiency for different water-quality limits for the Monte Grande well.

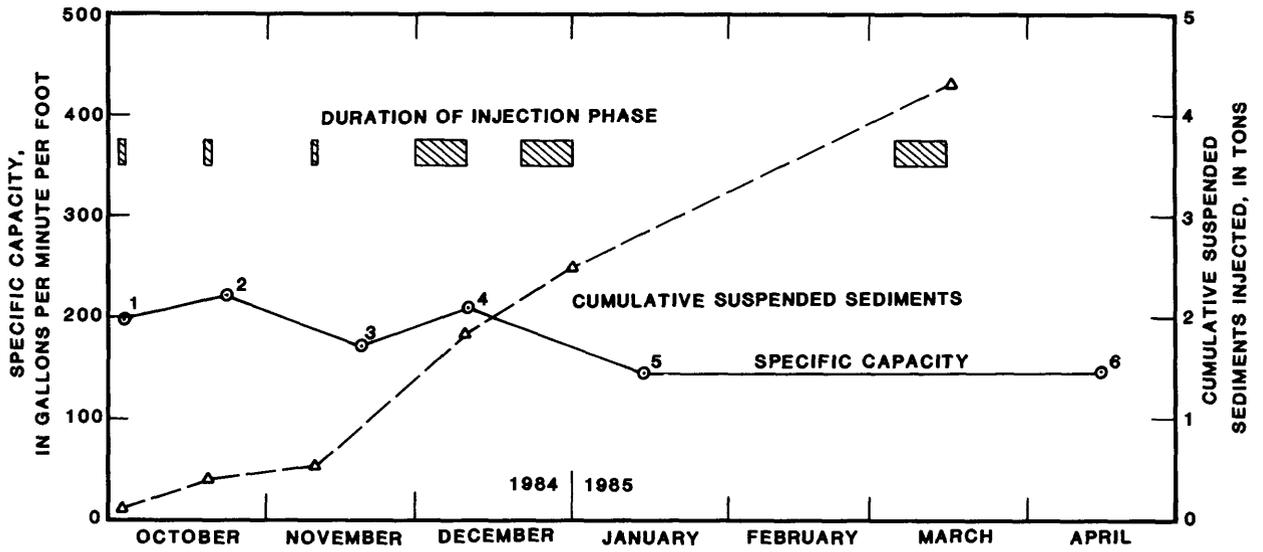


Figure 10.--Cumulative suspended sediment injected and changes in the specific capacity of the Monte Grande well as the injection-recovery tests proceeded.

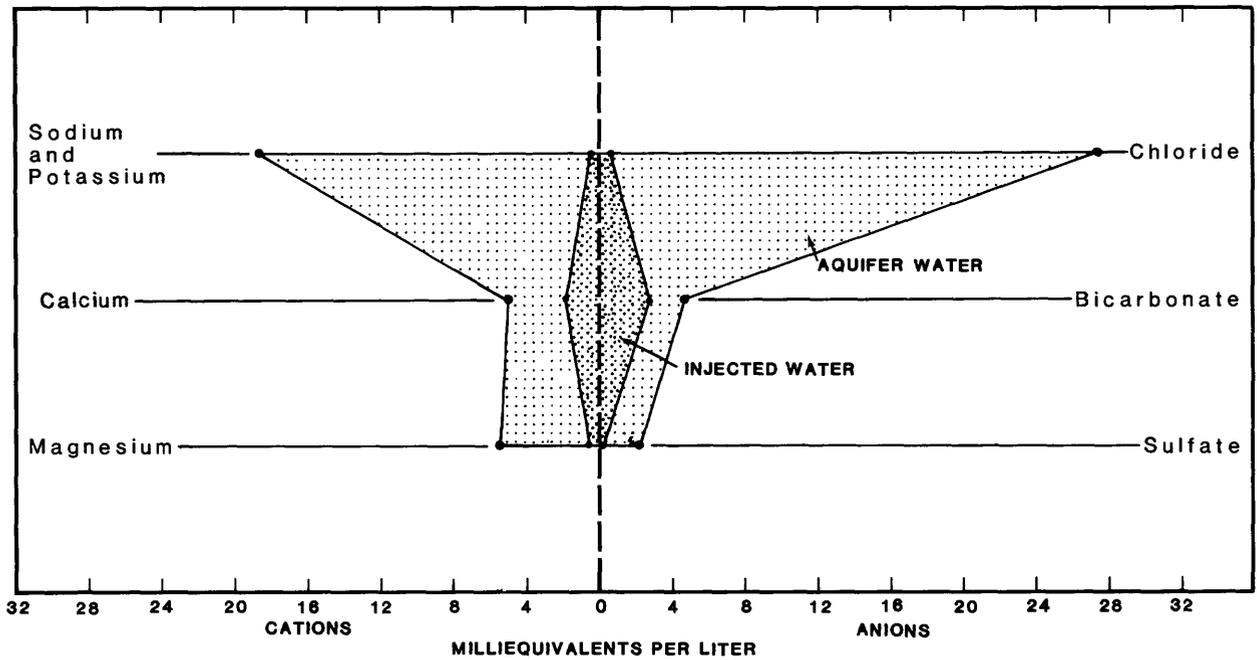


Figure 11.--Major dissolved inorganic constituents of the injection and aquifer water, in milliequivalents per liter.

Table 2. Physical properties and chemical characteristics of injection and aquifer waters.

[Constituents in milligrams per liter unless otherwise stated; ug/L = micrograms per Liter, uS/cm = microsiemens per centimeter at 25 °C]

Constituent		Injected water	Aquifer water
Silica	SiO ₂	17	18
Iron	Fe (ug/L)	9	40
Calcium	Ca	39	100
Magnesium	Mg	5.7	66
Sodium	Na	9.6	420
Potassium	K	1.5	14
Bicarbonate, field	HCO ₃	139	236
Sulfate	SO ₄	12	110
Chloride	Cl	17	970
Fluoride	F	0.1	0.2
Nitrite + Nitrate	NO ₂ + NO ₃	0.72	0.72
Phosphorus	PO ₄	0.03	0.04
Specific conductance, field (uS/cm)		260	3180
Temperature (°Celsius)		27	28
pH (standard units)		7.9	7.5
Manganese	Mg (ug/L)	14	30
Total dissolved solids (TDS)		241	1935

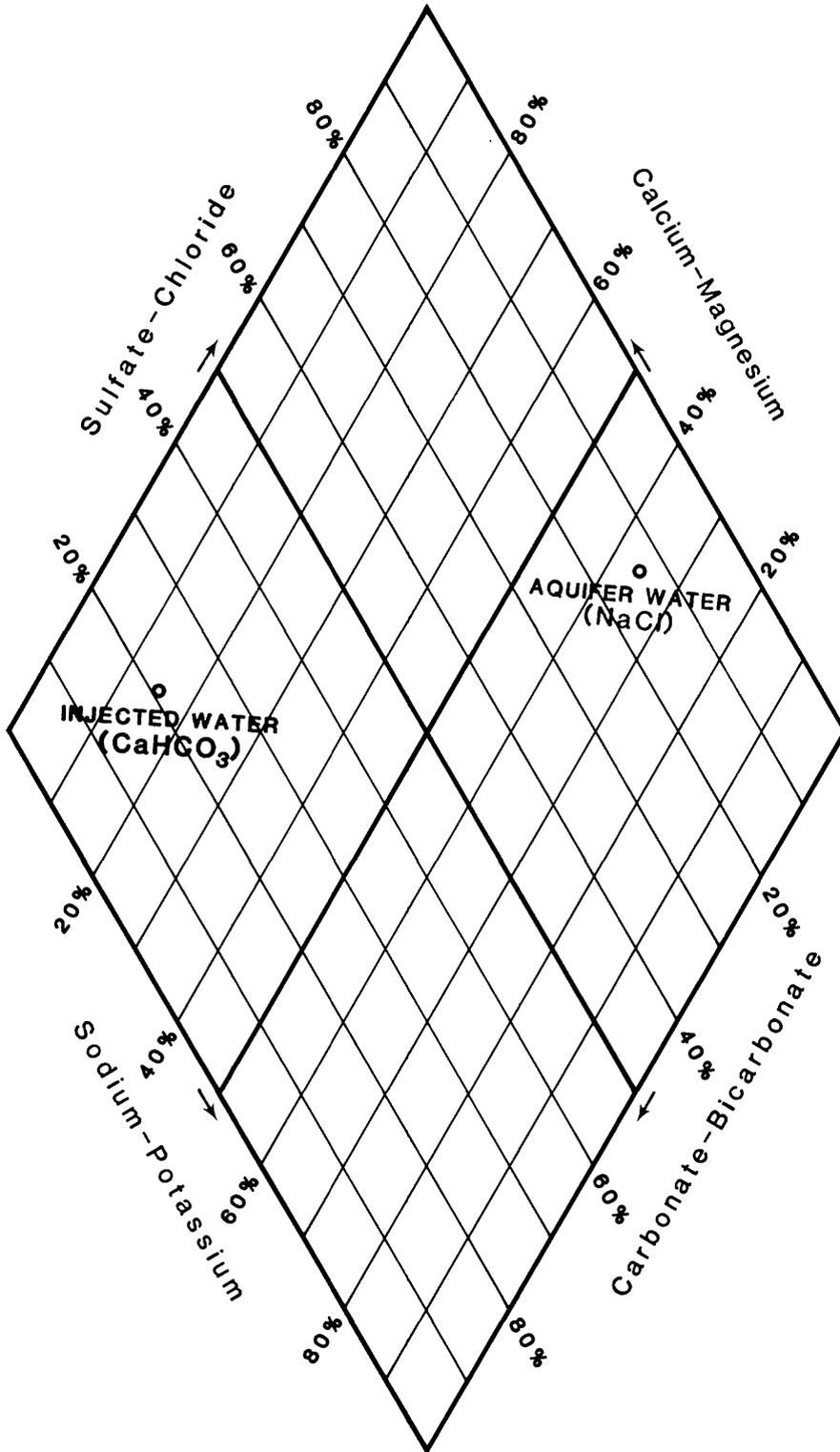


Figure 12.--Chemical classification of the Injection and aquifer waters.

place. If the logarithm of (K_{iap}/K_{eg}) (which is commonly known as the saturation index (SI)) is equal to 0, the water is in equilibrium with the mineral. If the ratio is a negative value, the water is undersaturated and the mineral can dissolve. If the logarithm of the ratio is a positive value, the water is super-saturated and mineral precipitation would be possible.

Equilibrium calculations were made for the injection and aquifer waters (table 3). The equilibrium calculations were made using WATEQF, a computer program to calculate chemical equilibria (Plummer, Jones, and Truesdell, 1978). Non-redox reactions were assumed for the equilibria computations. These calculations indicated that the injection water is supersaturated with calcite, in equilibrium with aragonite and dolomite, and undersaturated with the remaining minerals included in table 3. The assumption implies that the injection water, upon entering the aquifer and mixing with the aquifer water, may increase the potential for calcite precipitation because

both waters seem to be supersaturated with calcite. The aquifer water might be supersaturated with calcite, dolomite, aragonite, and magnesite and undersaturated with gypsum, anhydrite, fluorite, and siderite (table 3). A balance between precipitation and dissolution of these minerals may occur within the aquifer.

Although the injection water is supersaturated only with calcite, this does not imply that a mix of injected and aquifer waters would be at equilibrium or undersaturated with respect to the other minerals (dolomite, aragonite, and magnesite) with which the aquifer water can be supersaturated. There exists a series of thermodynamic and kinetic factors (chemical characters of the solution, the mineral, CO_2 partial pressures, differences in temperature, and a widely differing chemical compositions) that may produce a supersaturated original solution or undersaturated mixture from saturated original solutions (Wigley and Plummer, 1976).

Table 3. Saturation Index (SI $\text{Log}(K_{iap}/K_{eg})$) for some minerals commonly found in limestone.

Mineral	Formula	Injection water	Aquifer water
Calcite	$CaCO_3$	0.238	0.240
Dolomite	$CaMg(CO_3)_2$	0.016	0.693
Aragonite	$CaCO_3$	0.096	0.099
Siderite	$FeCO_3$	-28.835	-27.380
Magnesite	$MgCO_3$	-0.597	0.076
Fluorite	CaF_2	-2.847	-2.201
Gypsum	$CaSO_4 \cdot 2H_2O$	-2.625	-1.676
Anhydrite	$CaSO_4$	-2.823	-1.863

EVALUATION OF SINGLE-WELL INJECTION-RECOVERY PROCEDURE

A brief evaluation of the single-well injection-recovery procedures used in this study is given below:

●Injection procedures:

The Monte Grande well, which is open to both alluvium and Aymamón Limestone, is not ideal for this type of operation. A well open only to the best water-bearing unit would be more efficient as an injection-recovery well; injection rates at the Monte Grande well could be increased if modifications to increase the water levels at the control box were made.

●Analytical technique:

Although useful, the empirical approach used for this study is not the best technique and is limited by several conditions. A mathematical synthesis was not possible because of the lack of hydrogeologic information required for such analyses. Further studies need to be directed toward the implementation of analytical or digital models, which would require the collection of more data and an improved knowledge of aquifer characteristics that control the migration of injected water, such as hydrodynamic dispersion and diffusivity. The implementation of digital deterministic models would be necessary for a thorough understanding of cause and effect.

●Recovery efficiency:

The maximum recovery efficiency varied from 10 to 50 percent for the six tests; the mix recovery efficiency would depend on the desired quality of the recovered water.

●Water quality:

The accumulation of injected sediments decreased the well specific capacity; treatment, such as settling tanks and filtration, of the injected water could be implemented for further studies. Calculation of chemical equilibrium indicate that precipitation of calcite, dolomite, aragonite, and magnesite are possible, which may lead to a decrease in the aquifer transmissivity around the well. The addition of reactants to the injection water might be an alternative to delay the precipitation of such minerals and provide a longer life for the injection-recovery well.

●Feasibility:

Although these tests indicated that a reasonable percentage of the potable mix can be recovered, further studies would be necessary to test the effect of

large-scale freshwater injection and different injection-recovery cycles. The efficiency of different arrangements of injection and recovery wells also needs to be tested.

SUMMARY AND CONCLUSIONS

Artificial recharge would be helpful in increasing aquifer storage and in controlling the inland migration of saline water. Six injection-recovery tests were made to determine the feasibility of artificially recharging freshwater to the alluvium-Aymamón aquifer by injection through the Monte Grande well. Water from Río Grande de Arecibo diverted by an irrigation canal was used for injection. Injected volumes ranged from 0.6 to 6.6 million gallons. The storage period ranged from 6 minutes to nearly 31 days. Injected water recovered during the tests ranged from 0.12 to 2.1 million gallons. Graphical projections were used to predict the maximum recovery efficiency for various combinations of injected volumes and storage periods. Predicted maximum recovery efficiency generally was less than 60 percent. The transmissivity of the aquifer ranges from 55,000 to 80,000 ft²/d. The injection-recovery tests were made for different injected volumes and storage periods. Injection flow rates ranged from 300 to 456 gal/min. Pumping rates for recovery were approximately 380 gal/min. A chloride-load accounting approach was used to determine indirectly the maximum amount of injected water recovered.

A decrease in the specific capacity of the well (about 25 percent) indicated that sediment injected during the tests might be plugging the slotted well screen in the section tapping the alluvium. The chemical contrast between the injection and aquifer waters may lead to chemical reactions (precipitation or dissolution) that can change the well specific capacity or aquifer transmissivity. The injection water might be supersaturated with calcite and the aquifer water with calcite, dolomite, aragonite, and magnesite. Supersaturation might lead to precipitation of the mineral and, as a consequence, obstruction of void spaces, which would decrease the aquifer transmissivity in the vicinity of the well bore.

An evaluation of the single-well injection-recovery procedure reflects that: 1) A well open only to the best water-bearing unit would be more efficient as an injection-recovery well, 2) the empirical approach is not the best technique and is limited by several condi-

tions, 3) further studies need to be directed toward the implementation of analytical or digital models, and 4) although these tests indicated that a reasonable percentage of the potable mix can be

recovered, further studies would be necessary to test the effect of large-scale freshwater injection and different injection-recovery cycles.

SELECTED REFERENCES

- Bear, Jacob, and Jacobs, Martin, 1965, On the movement of water bodies injected into aquifer: *Journal of Hydrology*, Vol. 3, no. 1, 37-57 p.
- Giusti, E.V., 1976, Water resources of the north coast limestone area, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 42-75, 42 p.
- Gómez-Gómez, Fernando, 1984, Water resources of the lower Río Grande de Manatí valley, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 83-4199, 42 p.
- Kennedy, E.J., 1983, Computation of continuous records of streamflow: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3, Chapter A13, p. 53.
- Merritt, M.L., Meyer, F.W., Sonntag, W.H., and Fitzpatrick, D. J., 1983, Subsurface storage of freshwater in south Florida: A prospectus: U.S. Geological Survey Water-Resources Investigations Report 83-4214, 69 p.
- Pettyjohn, W.A., 1981, Introduction to artificial ground-water recharge: Robert S. Kerr Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Ada, Oklahoma, 44 p.
- Plummer, L.N., Jones, B.F., and Truesdell, A.H., 1978, WATEQF - A fortran IV version of WATEQ, A computer program for calculating chemical equilibrium of natural waters: U.S. Geological Survey Water-Resources Investigations Report 76-13, 63 p.
- Quiñones-Aponte, Vicente, 1986, Water resources of the lower Río Grande de Arecibo valley: U.S. Geological Survey Water-Resources Investigations Report 85-4160, 39 p.
- Reeder, H.O., Wood, W.W., Ehrlich, G.G., and Sun, R. J., 1976, Artificial recharge through a well in fissured carbonate rock, West St. Paul, Minnesota: U.S. Geological Survey Water-Supply Paper 2004, 80 p.
- Santiago-Vázquez, Flaherty, and Giavara, 1982, Water supply plan: North Coast Area "Executive Summary": Puerto Rico Aqueducts and Sewer Authority, 38 p.
- Torres-González, Arturo, and Díaz, J.R., 1984, Water resources of the Sabana Seca to Vega Baja area: U.S. Geological Survey Water-Resources Investigations Report 4115, 53 p.
- Whitesides, D.V., Quiñones-Aponte, Vicente, and Zack, Allen, 1985, Estimating the capacity of a salty limestone aquifer in Puerto Rico to receive, store, and release injected freshwater using chloride mass balance: Proceedings of the International Symposium on Tropical Hydrology and 2nd Caribbean Islands Water Resources Congress, San Juan, Puerto Rico, May 5-8, 1985, American Water Resources Association Technical Publication Series TPS-85-1, p. 50-55.
- Wigley, T.M.L., and Plummer, L.N., 1976, Mixing of carbonate water: *Geochimica et Cosmochimica Acta.*, vol. 40, pp. 989-995.
- Zack, A.L., and Class-Cacho, Angel, 1984, Restoration of freshwater in the Caño Tiburones area, Puerto Rico: U.S. Geological Survey Water-Resources Investigations Report 83-4071, 33 p.