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# HYDROCHEMISTRY OF THE SOUTH COASTAL PLAIN AQUIFER SYSTEM OF PUERTO RICO AND ITS RELATION TO SURFACE WATER RECHARGE NAVAL ACTIVITY PUERTO RICO

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# HYDROCHEMISTRY OF THE SOUTH COASTAL PLAIN AQUIFER SYSTEM OF PUERTO RICO AND ITS RELATION TO SURFACE WATER RECHARGE

Fernando Gómez-Gómez[1]

**ABSTRACT:** The ground-water resources within the South Coastal Plain of Puerto Rico between Ponce and Patillas have been intensively developed as an irrigation water source since about 1910. In 1987, consumptive withdrawals from this aquifer system were estimated at 274,000 cubic meters per day, with 67 percent used for irrigation and the remainder mostly used for public water supply. The development of the ground-water resources and changes in land use have altered the existing ground-water flow system. Among these changes are a substantial reduction in surface water irrigation, increased use of ground-water drip irrigation and an overall reduction in irrigated farmland. As a result of these changes, aquifer recharge from surface water sources has been reduced significantly. This is expected to result in a gradual upconing of lower quality ground water and seawater intrusion and eventually in deterioration in the quality of ground water in the area.
**KEY WORDS:** Puerto Rico; Ground water; Ground-water quality; Isotope hydrology.

## INTRODUCTION

### Purpose and Scope

A regional appraisal of the South Coastal Plain aquifer system between Ponce and Patillas was initiated in 1986 as part of the Caribbean Islands Regional Aquifer Systems Analysis program (CI-RASA; Gómez-Gómez, 1987). One of the general purposes of the CI-RASA was to describe the hydrochemistry of the aquifer system; the more specific objectives of this part of the study are to:

- define areas which may have undergone a significant change in ground-water quality as determined from review of available ground-water quality data,
- relate changes in concentration of major constituents in ground-water to the flow system, and
- anticipate the effect on the hydrochemistry, which can result from on-going hydrologic modifications.

The approach used to achieve the objectives of the hydrochemistry study includes:

- Compiling and developing a computerized data base to manage analyses from 1,650 samples obtained at 520 wells between 1929 and 1980.
- Collecting and analyzing water samples from 100 wells, and 20 streams and canals to define existing water quality. Field determinations were made for specific conductivity, temperature, pH, and alkalinity. Water samples collected at these sites were analyzed for calcium, magnesium, sodium, potassium, sulfate, chloride, fluoride, silica, and the stable isotopes of hydrogen and oxygen.
- Developing maps showing the distribution of dissolved solids concentrations and the percent of recharge water derived from surface water sources.
- Developing maps showing the areal variation in hydrochemical facies.
- Using the results of the above analysis in conjunction with the ground-water flow models developed as part of the CI-RASA program to anticipate future changes in the hydrochemistry.

This paper describes the hydrochemistry of the study area and the relation between water chemistry and recharge sources.

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## Description of the Study Area

### Physical Setting

The South Coastal Plain geographic area of Puerto Rico (Pico, 1964) covers an area of 47,400 ha (hectares) (fig. 1). This area lies within a rain shadow formed by the Cordillera Central and its easternmost extension, the Sierra de Cayey. These mountains rise to an altitude averaging 700 m (meters) and extend about 65 km (kilometers) along the northern edge of the coastal plain, forming an effective barrier to the predominantly northeast trade winds. Rainfall averages 1,000 mm/yr (millimeters per year), but in general ranges from about 1,500 mm/yr near Guayama to about 900 mm/yr throughout most of the plain west of Santa Isabel. Pan evaporation averages 2,000 mm/yr and most of the rainfall is lost to evapotranspiration. The scarce rainfall and mean annual temperature of 26°C contribute to maintaining a soil moisture content too low for cultivation of crops in areas not served by the extensive irrigation infrastructure. In areas not irrigated, savannahs consisting largely of scrub vegetation predominate. Land use is largely for agricultural purposes, but total cultivated land area has declined from 31,300 ha in 1969 to approximately 13,200 ha in 1987. Urban development in 1980 covered approximately 5,300 ha mostly in the vicinity of Ponce (pop. 189,046) and Guayama (pop. 40,183).

### Hydrology

All streams crossing the South Coastal Plain have intermittent flow. Streamflow discharge records indicate that in a typical year flows that equal or exceed about 2.8 $m^3/s$ (cubic meters per second) (storm runoff event on the south coast) occur on an average of nine days per year (2.5 percent of the time). The Río Grande de Patillas, which has a larger drainage area and drains the more humid eastern part of the south coast watershed, exceeds this flow rate about 10 percent of the time (table 1).

Table 1.--*Basic streamflow statistics for unregulated streams in the South Coastal Plain*

| Station number | USGS number | Drainage area, $km^2$ | Years of record | Percent of time flow equal to or greater than 2.8 $m^3/s$ | Percent of time flow equal to or less than 0.6 $m^3/s$ |
|---|---|---|---|---|---|
| Río Grande de Patillas | 50092000 | 47.4 | 16 | 10 | 33 |
| Río Descalabrado | 50108000 | 33.4 | 3 | .6 | 96 |
| Río Inabón | 50112500 | 25.1 | 19 | 2.5 | 75 |
| Río Portugués | 50115000 | 22.8 | 18 | 2.0 | 78 |

The hydrology of the South Coastal Plain has been modified from its natural state mostly through construction of irrigation projects. The earliest project dating back to about 1825 consisted of diversion of baseflow of the principal streams at points where the streams entered the alluvial fans. However, the most significant changes were made between 1910 and 1935 when a network of 190 km of irrigation canals and laterals, six reservoirs with a total storage capacity of 50 $hm^3$ (cubic hectometers), and two tunnels across the insular hydrologic divide made available an average of 300,000 $m^3/d$ (cubic meters per day) to approximately 10,800 ha of previously uncultivated land east of Río Jacaguas (Toro-Lucchetti, 1963; fig. 1). An irrigation network of canals and reservoirs had been constructed west of Río Jacaguas by the end of the 1800's. This irrigation network diverted most of the baseflow of streams west of Río Jacaguas (about 100,000 $m^3/d$).

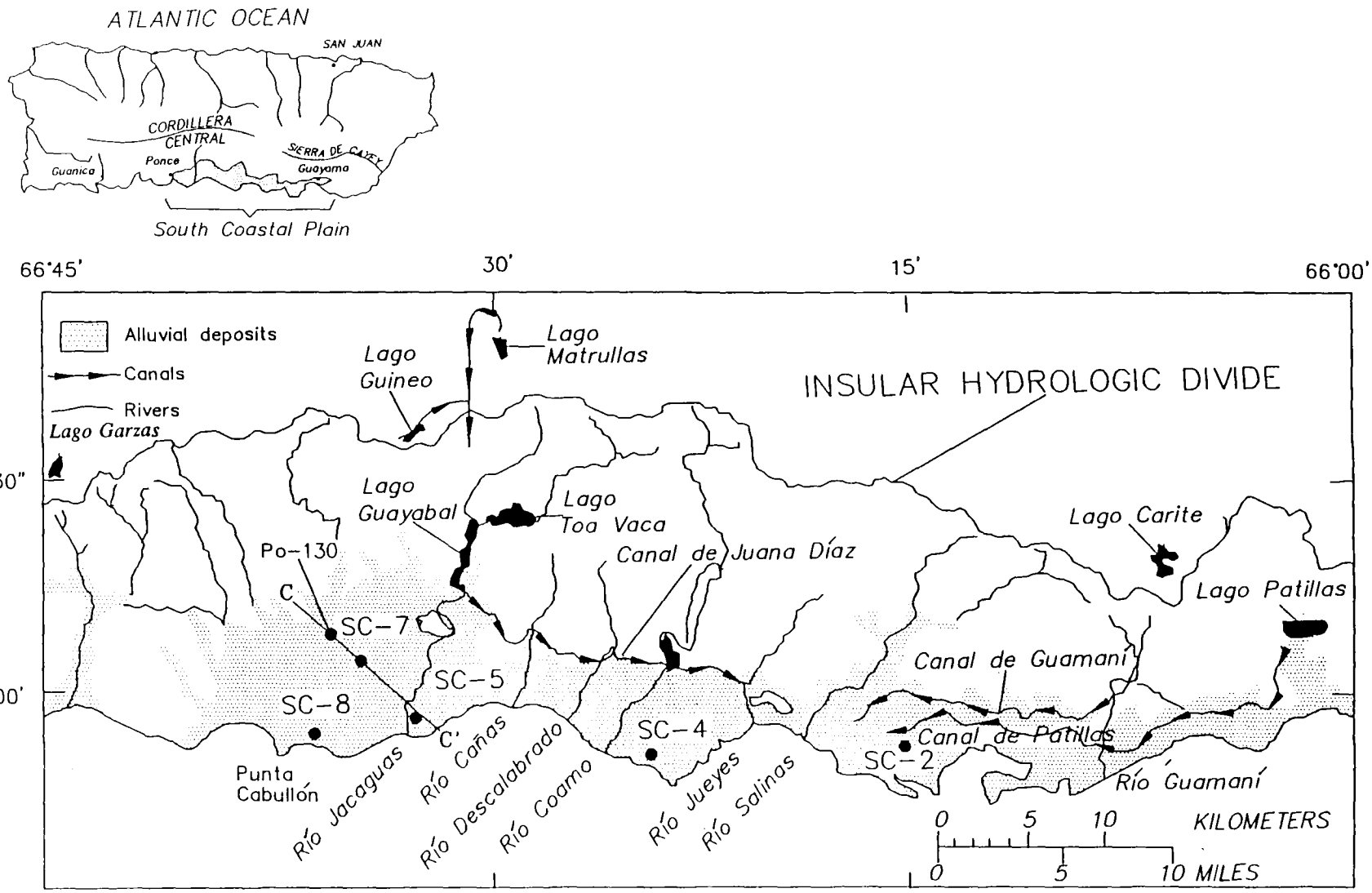



Figure 1.--Location and general features of the South Coastal Plain aquifer system and line of hydrogeologic cross-section C-C' in figure 2.

In 1982, total irrigation deliveries by government-operated irrigation districts east of Río Jacaguas averaged 99,000 $m^3/d$ (Torres-Sierra and Avilés, 1986); in the area west of Río Jacaguas, irrigation deliveries totaled an estimated 50,000 $m^3/d$. The reduction in surface water diversions is directly related to the general decline of total acreage in sugarcane (the principal surface water-irrigated crop) and more recently to the general preference for using ground water for drip irrigation of truck-farm crops. On a regional basis, it is estimated that 30 percent of the applied surface water recharges the aquifer (Bennett, 1976). Thus, it is possible that on the average, areal recharge may have been reduced by 70,000 $m^3/d$ between the early part of the century and the present.

Development of the aquifer as a source of irrigation water began in about 1900 by the use of steam-powered centrifugal pumps. By 1925, kerosene-driven motors had replaced steam and approximately 50 well batteries existed between Ponce and Guayama, yielding a total estimated mean discharge of 80,000 $m^3/d$. In 1930, electric-powered deep turbine pumps began replacing the less efficient centrifugal pumps. Ground-water withdrawals increased rapidly after this date, reaching a peak of 360,000 $m^3/d$ in 1947. Since then, ground-water irrigation withdrawals have continuously declined to an estimated 130,000 $m^3/d$ at present. About 17 percent of that total (60,600 $m^3/d$) is used for drip irrigation, which is more efficient than furrow irrigation. Both drip irrigation and public water supply withdrawals (estimated at 80,000 $m^3/d$) are considered 100 percent consumptive, while withdrawals used in furrow irrigation are estimated as 70 percent consumptive. This indicates that the overall consumptive ground-water withdrawals in the South Coastal Plain is probably about 189,000 $m^3/d$, which represents a decrease of approximately 63,000 $m^3/d$ since 1947. On a regional basis this is about equal to the reduction in areal aquifer recharge, estimated at 70,000 $m^3/d$, resulting from the decline in use of surface-water for irrigation.

## Hydrogeology

Ground water occurs mostly in alluvial deposits and associated clastic sediments of Pleistocene to Miocene(?) age. The thickness of these deposits varies substantially. East of Río Jueyes, the bedrock unit consists of volcaniclastic and igneous rocks which have either undergone weathering during exposure, and have an irregular surface beneath the alluvial cover, or block faulting (Renken and others, 1990). As a result, the depth of unconsolidated deposits varies areally and within a given alluvial fan. Maximum thickness of these deposits is known to exceed 127 m at the Salinas fan. However, at depths of greater than about 50 m the deposits are less sorted and consist of stratified beds of fine to coarse sand or poorly sorted gravel and cobbles in a matrix of compacted shale. West of Río Jueyes, the thickness of unconsolidated deposits reaches a maximum known depth of 915 m, as determined by an oil test well near the mouth of Río Coamo (Glover, 1971). Possibly at about this location and toward the west, the unconsolidated deposits are underlain by carbonate rocks -- the Ponce Limestone (Miocene) and the Juana Díaz Formation (Oligocene) -- which thicken westward reaching a maximum known thickness of 380 m at the coastline near Ponce (Glover, 1971). Between the western limit of the coastal plain and Río Jacaguas, the aquifer exists both in the unconsolidated deposits and in the carbonates, which seem to have developed significant secondary porosity in the more inland areas (fig. 2).

# METHODS OF ANALYSIS

Samples were obtained at 100 wells and 20 surface water sites during March to April 1986 (area east of Río Jueyes) and during April to May 1987 (area west of Río Jueyes). These months are typically near the end of the relatively dry weather "season" and represent the most stable hydrologic conditions of streamflow (low-flow) and operation of the irrigation system. Samples for water quality analyses were obtained in conjunction with a synoptic survey of hydrologic conditions, which included the following measurements: discharge measurements at all major irrigation and public water supply wells and estimates of their mean daily discharge; discharge measurements at selected streams and canals and delineation of saturated (wet) segments; water-level measurements at wells; and, delineation of irrigated acreage. Data were used to develop potentiometric surface maps at a scale of 1:20,000 for the entire South Coastal Plain aquifer system. These potentiometric surface maps were essential in defining ground-water flow paths.

## Definition of Aquifer Recharge Sources

The stable isotopes deuterium and oxygen-18 were used in defining the percent of surface water derived from irrigation surface water diversions or streamflow in well water samples using techniques described by Muir and Coplen (1981). This estimate is obtained by defining the isotopic ratios of native ground water unaffected by surface water

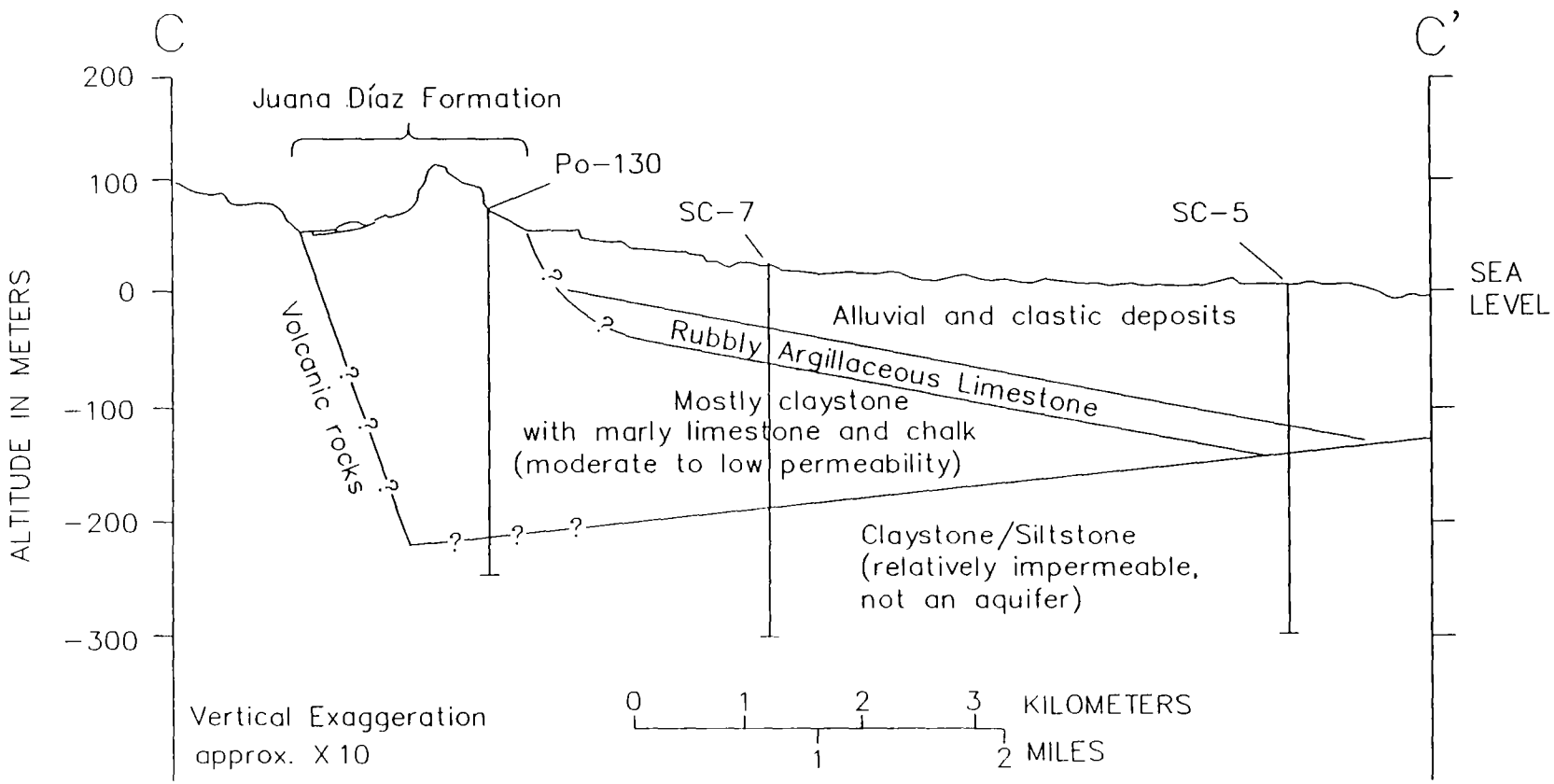



Figure 2.--Generalized hydrogeologic cross-section of the aquifer at Ponce.

recharge, where rainfall infiltration is the only source of aquifer recharge, and of surface water infiltrating the aquifer system. Three wells within the Salinas fan were sampled on three separate occasions between March 1986 and May 1989 to define the stable isotopic compositions for native ground water in the alluvial deposits.

The average isotopic compositions for deuterium (D) and oxygen -18 ($^{18}O$) in a total of four samples of native ground water were:

$$\delta D = -21.5\ \% \pm 1.3\ ‰$$

$$\text{and } \delta^{18}O = -3.7\ \% \pm 0.4\ ‰$$

The three wells were selected because it is the only part of the coastal plain not served by the irrigation canal system. The land has been left fallow for about 10 years (no irrigation effects), and the local potentiometric surface gradient excludes the possibility of streamflow seepage toward these wells (Quiñones-Aponte and Gómez-Gómez, 1987). The variability of isotopic compositions in well water samples was tested by sampling 13 wells in the area east of Río Jueyes during August 1986 (four months after these were first sampled). The results obtained indicated a variability of less than 1.0 ‰ in deuterium and of less than 0.4 ‰ in oxygen -18. The aquifer in this part of the coastal plain has a theoretical water renewal rate of about 10 years. A more appropriate analysis of variability of the isotopic ratios in ground water would require sampling at intervals of about one year under constant hydrologic conditions.

In defining the isotopic compositions for surface water recharge, a total of 23 samples were obtained between March 1986 and May 1989 at ten major surface water sources, which included the principal streams, canals and two reservoirs near the insular hydrologic divide (table 2). The average isotopic compositions for the 23 samples of surface water were

$$\delta D = -10.1\ \% \pm 2.4‰$$

$$\text{and } \delta^{18}O = -2.6\% \pm 0.5‰$$

Table 2.--*Deuterium and oxygen-18 isotopic composition in selected surface water sources flowing into the South Coastal Plain (deuterium and oxygen-18 values in parts permil referred to SMOW; Standard Mean Ocean Water)*

| SOURCE | $\delta D \pm \sigma$ | $\delta^{18}O \pm \sigma$ | Number of samples | Number of stations |
|---|---|---|---|---|
| Canal de Patillas | -7.7 ± 1.1 | -2.2 ± 0.4 | 5 | 3 |
| Canal de Guamaní Oeste | -11.9 ± 3.0 | -2.9 ± 0.4 | 5 | 3 |
| Canal de Juana Díaz | -9.8 ± 3.6 | -2.4 ± 0.6 | 3 | 2 |
| Intrabasin reservoirs * | -10.3 ± 2.5 | -2.4 ± 0.4 | 3 | 3 |
| Río Grande de Patillas | -11.5 -- | -2.8 -- | 1 | 1 |
| Río Guamaní | -10.3 ± 1.0 | -2.8 ± 0.4 | 3 | 2 |
| Río Coamo | -10.0 ± 0.7 | -2.7 ± 0.6 | 2 | 1 |
| Río Descalabrado | -10.0 -- | -2.3 -- | 1 | 1 |
| All Sites | -10.1 ± 2.4 | -2.6 ± 0.5 | 23 | 16 |

* Lago Carite and Lago Garzas

The isotopic compositions have a higher variability in surface water than in native ground water. However, the signatures are sufficiently distinct to make this technique feasible for obtaining estimates of surface water recharge. It is possible that the isotopic signature of surface water in the principal streams during storm runoff events may differ from the the signatures obtained during low flow conditions. However, aquifer recharge during storm flow events accounts for no more than 15 percent of the annual streamflow recharge within any of the alluvial fans. This estimate is based on field tests made in the Río Loco valley at Guánica (west of Ponce) where a controlled release from a reservoir was maintained for a duration of 28 days at an average discharge rate of 6.8 $m^3/s$ (McClymonds, 1967). That test was conducted within a heavily pumped aquifer having similar stream deposits and transmissivities comparable to the Río Coamo and Salinas fans. The results obtained indicated an av-

erage infiltration rate of 0.18 cubic meters per second per kilometer of stream channel. If this rate of streamflow infiltration is assumed to be the maximum for streams in the coastal plain during storm runoff events, it would represent about 15 percent of the annual mean streamflow aquifer recharge in the Río Coamo and in the Salinas fans according to digital flow model simulation. Both of these alluvial fans are the most heavily pumped areas within the South Coastal Plain aquifer system.

Plots of $\delta D$ versus $\delta^{18}O$ were prepared for analyses from well samples, which were grouped into four sub-areas, each with similar hydrologic and hydrogeologic characteristics. These are

(a) the area west of Río Cañas,
(b) the area from Río Cañas to Río Jueyes,
(c) the area of the Salinas fan,
(d) the area east of the Salinas fan.

Within these areas, the relation between $\delta D$ and $\delta^{18}O$ is generally on a slope less than that of the local meteoric water line (MWL) as defined at a station near San Juan as part of the Caribbean Islands RASA program (fig. 3). A slope less than that of the local MWL is an indication of evaporation of rainfall prior to reaching land surface (a local effect) or after impact, either at or below the soil surface. Insufficient data have been obtained in the south coast to determine which is the dominant effect. If evaporation takes place after the water has reached the aquifer, either by direct evaporation from the water table or as a result of recycling of applied irrigation water, then there will be an error in the calculations.

Regional estimates of the percentage of aquifer recharge derived from surface water infiltration were made using $\delta D$ values obtained for water samples at wells. The calculation was made using the following equation:

$$\text{Percent surface water derived recharge} = \frac{(\delta D_{gw}) - (\delta D_{w})}{(\delta D_{gw}) - (\delta D_{sw})} \times 100$$

where,
$\delta D_{gw}$ is the deuterium signature determined for native ground water or -21.5‰
$\delta D_{w}$ is the deuterium value for the well water sample, and
$\delta D_{sw}$ is the deuterium signature determined for surface water or -10.1‰
Similarly, calculations can be made using the $^{18}O$ values as follows:

$$\text{Percent surface water derived recharge} = \frac{(^{18}O_{gw}) - (^{18}O_{w})}{(^{18}O_{gw}) - (^{18}O_{sw})} \times 100$$

where,
$\delta^{18}O_{gw}$ is the oxygen-18 signature determined for native ground water, or -3.7‰,
$\delta^{18}O_{w}$ well is the oxygen-18 value for the well water sample, and
$\delta^{18}O_{sw}$ is the oxygen-18 signature determined for surface water, or -2.6‰.

If evaporation of recharge water is insignificant, the estimates obtained using both equations should be similar. This was generally the case throughout the alluvial fans except in parts of the coastal plain east of Río Guamaní.

Maps showing the estimated percent surface-water-derived ground water were prepared using only those values (well sites) in which calculations using both $\delta D$ and $\delta^{18}O$ gave comparable estimates (fig. 4a and b). The regionalized contour lines probably are within 15 percent of the calculated value at specific well locations (table 3). West of Río Cañas, the estimated percent surface-water-derived ground water at wells do not show a pattern that can be contoured. The results only indicate a general decrease from about 90 percent surface-water-derived aquifer recharge in the vicinity of Río Jacaguas to about 70 percent in the part of the aquifer west of Punta Cabullón. This is to be expected because surface-water-derived aquifer recharge throughout the Ponce urban area probably has declined as a result of increased diversions of streamflow for public water supply purposes and flood control channelization projects.

The regionalized estimates of surface-water-derived aquifer recharge indicate that the isotopic signatures defined for native ground water and surface water may be valid for most parts of the South Coastal Plain aquifer system at least as a first approximation. The major discrepancy in surface water recharge estimates using both equations was obtained in well water samples showing an enrichment in oxygen-18. This could indicate that evaporation of water applied as furrow irrigation is locally significant in some areas. The calculation of these estimates also did not include those data points, which plotted five percent above the MWL (indicating an enrichment in deuterium), because these figures could be erroneous and were not confirmed by re-sampling. Any shift in the isotopic signature of ground water resulting from mineral/rock interaction would be expected to cause a depletion of deuterium in the water because the $\delta D$ values of clays and other minerals in igneous, metamorphic, and sedimentary rocks vary between -80 to -30‰ (Kharaka and Carothers, 1986).

Discrepancies greater than 10 percent of the calculated percentage of surface-water-derived aquifer recharge using both equations generally occurred in well clusters. In the well clusters areas, oxygen-18 enrichment (possibly resulting from evaporation) may be occurring. This enrichment in isotopic composition was found in water samples

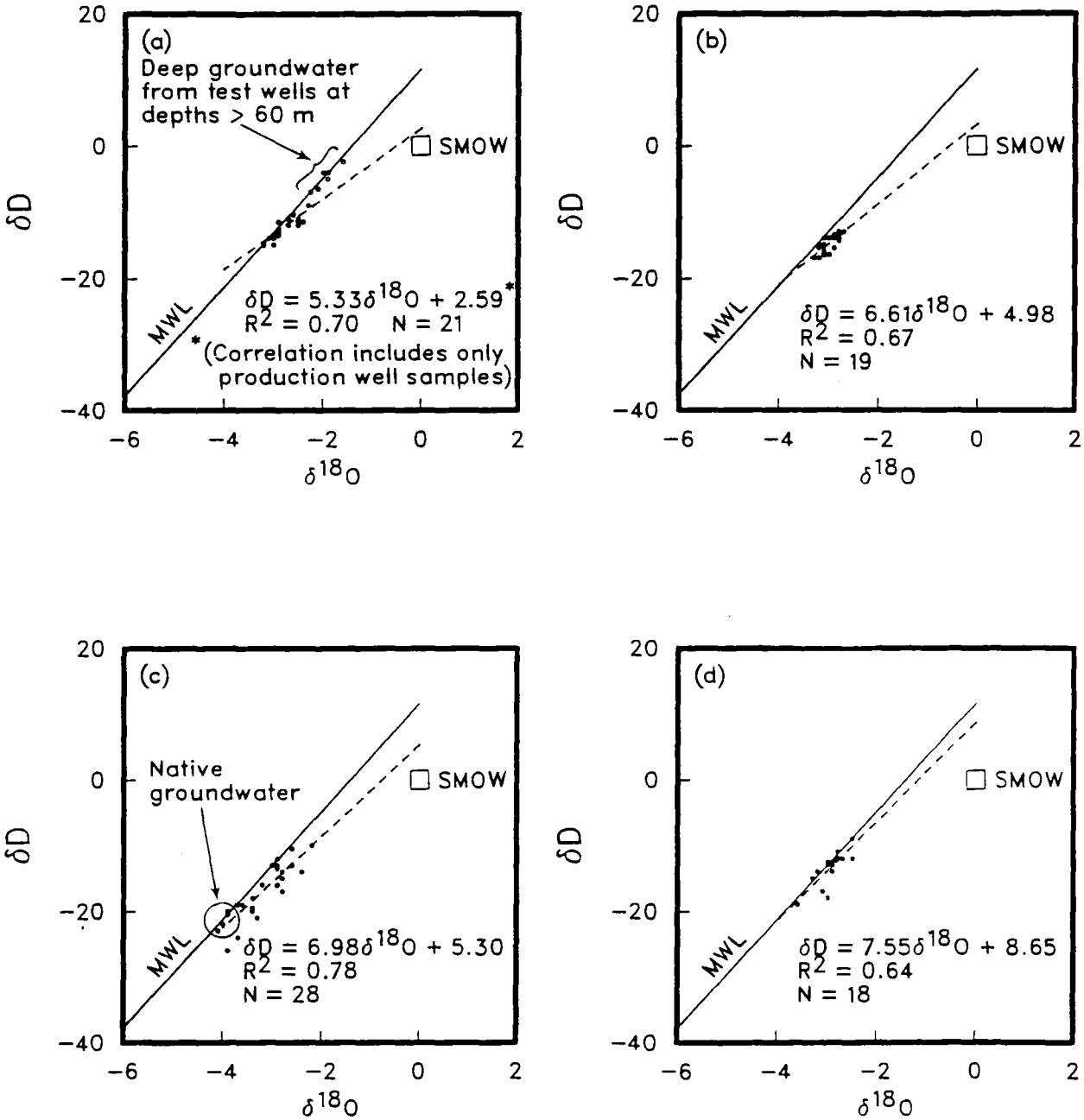



Figure 3.--$\delta^{18}O$-$\delta D$ relation for ground-water samples from: (a) area west of Río Cañas, (b) area between Río Cañas to Río Jueyes, (c) the Salinas fan, and (d) area east of the Salinas fan. SMOW indicates Standard Mean Ocean Water.

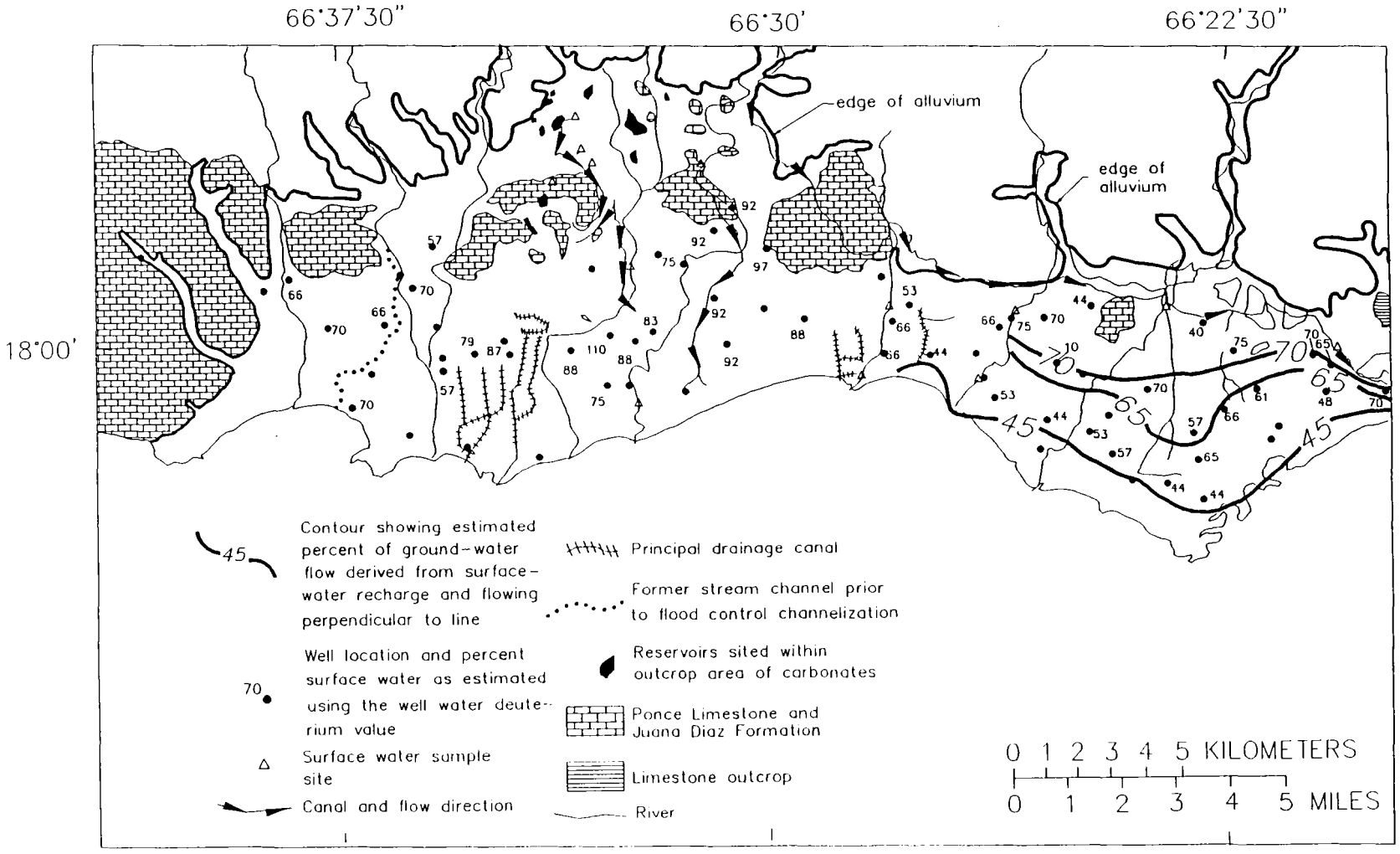



Figure 4(a).--Areal distribution of the estimated percent surface-water-derived ground water in area west of Río Jueyes.

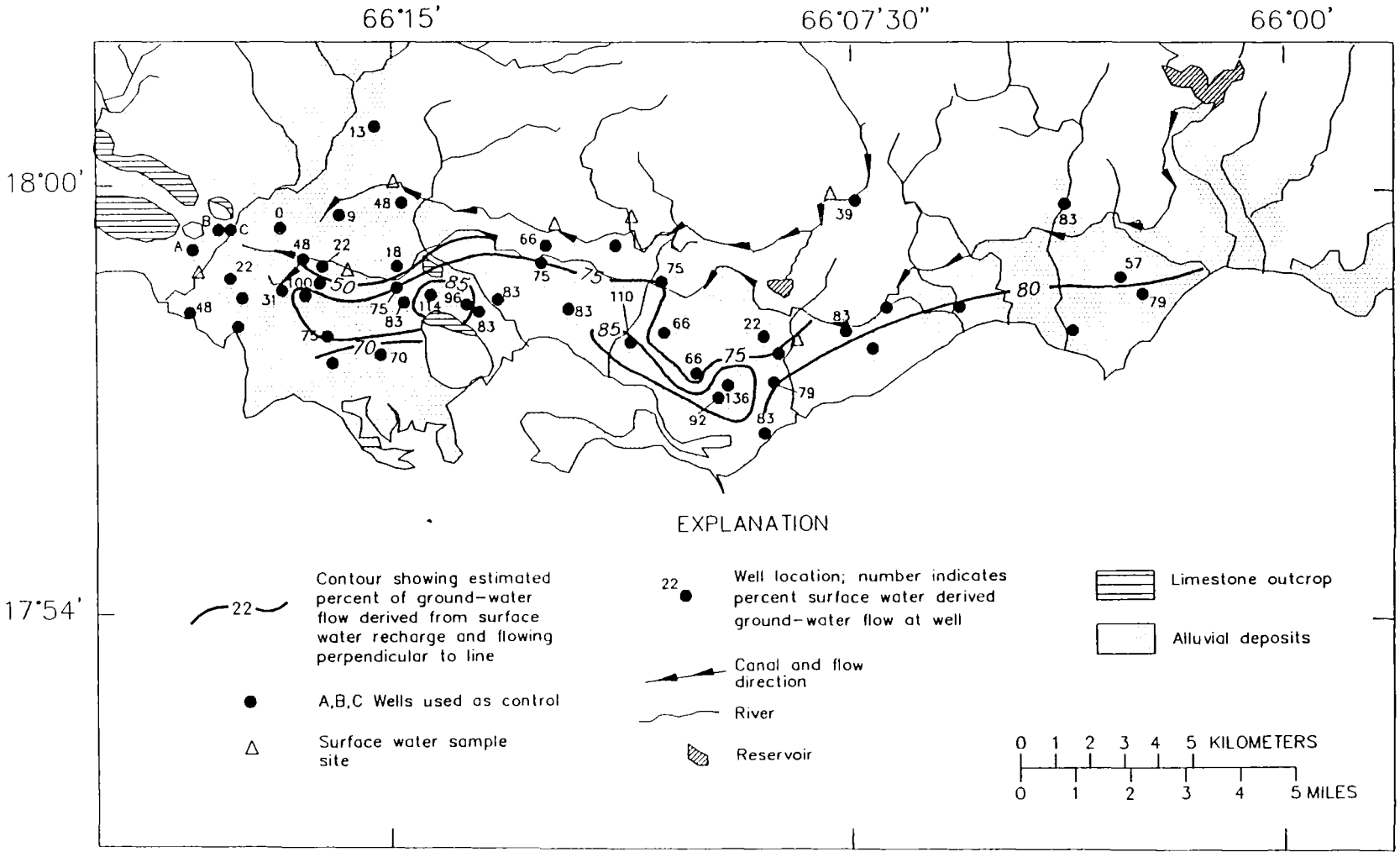



Figure 4(b).--Areal distribution of the estimated percent surface-water-derived ground water in area east of Río Jueyes.

Table 3.--*Percent difference obtained in calculating the percent surface-water-derived ground water at wells using either the deuterium or oxygen-18 values with the corresponding equation and regional estimates of δDsw or $\delta^{18}$Osw*

| SUB-AREA | Average percent difference in calculations * | | σ | Range in percent | Number of samples |
|---|---|---|---|---|---|
| Area west of Río Cañas | 11.1 | ± | 9.4 | 1 - 34 | 21 |
| Río Cañas to Río Jueyes | 10.1 | ± | 6.0 | 2 - 21 | 25 |
| Salinas fan | 12.5 | ± | 11.1 | 2 - 35 | 14 |
| Area east of Salinas fan | 10.3 | ± | 8.5 | 1 - 25 | 17 |
| All values | 10.7 | ± | 8.4 | 1 - 35 | 77 |

* absolute values

from most wells at the interfluvial area between Río Cañas and Río Descalabrado and in samples from wells east of Río Guamaní. In both areas, it is unlikely that significant evaporation occurs from the aquifer because ground water is locally confined. Therefore, evaporation is either occurring prior to aquifer recharge or during recycling of ground water applied for irrigation in areas up-gradient and within unconfined parts of the aquifer.

In the Ponce area, the estimates obtained at wells yielding water of a calcium-chloride type (discussed in a later section of this text) also indicated a significant discrepancy (as much as 30 percent) from the calculated percentage of surface-water-derived recharge. This difference in the calculations cannot be attributed to upward migration of deep ground water from the carbonate units because isotope signature of the deep ground water is essentially that of meteoric water with an average δD equal to -3.8‰ and $\delta^{18}$O equal to -1.8‰ (refer to fig. 3a). The water pumped at wells in the Ponce area apparently has undergone evaporation as a result of irrigation application and recycling to the subsurface. The source of this pumped well water is possibly a combination of ground water originating from the upper part of the alluvium (<45m) and from the underlying carbonate units.

Stable isotope analyses of ground-water samples collected during deep drilling through the carbonate units at SC-5 and SC-7 test wells near Ponce (refer to figs. 1 and 2) indicate that aquifer recharge could be occurring throughout the outcrop areas of the Juana Díaz Formation and Ponce Limestone at the western part of the South Coastal Plain aquifer system. The source of the recharge could be direct rainfall infiltration or seepage from reservoirs located within the outcrop area of the carbonate units (locations shown in fig. 4a and b). The latter is the most probable source because it is unlikely that ground water in the upland carbonates, derived exclusively from rainfall recharge, would have an isotope signature more enriched than that prevalent in the water table aquifer contained within the more humid and karstified limestone units of the North Coast Ground-Water Province of the island. The isotopic compositions for four ground-water samples obtained during test well drilling through the south coast carbonates were as follows:

δD of - 3.8‰ ± 1.1‰
and $\delta^{18}$O of - 1.8‰ ± 0.2‰

For comparison, the isotopic compositions for 14 water samples from the north coast karst limestones are:

δD of - 9.1‰ ± 2.3‰
and $\delta^{18}$O of - 2.7‰ ± 0.3‰

Leakage from the reservoirs could constitute a significant source of recharge to the unconsolidated deposits through deep circulation of ground water. Upward migration of ground water originating from aquifer recharge in the general area of the reservoirs seems to occur in parts of the coastal plain in which wells are essentially nonexistent. This may be inferred both from the potentiometric surface distribution (Rodríguez-del-Río and Quiñones-Aponte, 1990) and the variation of head with depth at test wells SC-7 and SC-5. At test well SC-7, located within the northern part of the coastal plain, the head in the aquifer decreased from about 10.5 m above mean sea level at the water table surface to 4.6 m above mean sea level at a depth of 156 m below the water table. At test well SC-5, located near the coast, the head increased from 1.5 m above mean sea level (land surface altitude) to about 11.5 m above mean sea level at a depth of 150 m below land surface within the rubbly limestone beneath the alluvium.

## Ground-Water Quality

Maps showing the distribution of the concentration of dissolved solids in ground water reflect the complex nature of the aquifer system (fig. 5a and b). The lowest concentrations of dissolved solids existed within the area east of Río Seco and are associated with the presence of predominately coarse grained alluvial deposits (high in sand, gravel, and cobbles) and the crystalline nature of relatively shallow pyroclastic bedrock units. Elsewhere, the variation in dissolved solids was influenced by:

(a) dilution by surface water derived from streams and the irrigation canals (during low flow the principal streams have dissolved solids concentrations of less than 400 mg/L (milligrams per liter) and the irrigation canals have concentrations less than 200 mg/L),

(b) upward migration of ground water from deeper parts of the aquifer system either through natural discharge or upconing, and

(c) interaction of groundwater with the minerals present in the aquifer matrix.

Within several areas, dissolved solids concentrations have increased from 200 to as much as 700 mg/L since the mid 1960's. The greatest increase has occurred at coastal areas near Ponce. A slight increase in dissolved solids may have occurred in parts of the Río Coamo and Salinas fans, but, in general, the increase in concentration in these areas has not been greater than 200 mg/L at wells for which previous analyses are available. Although most of the areas in which dissolved solids concentrations have increased are near the coast, the source of the dissolved constituents cannot be fully attributed to coastal saltwater encroachment. The relative importance of any of the above stated conditions on the hydrochemistry can initially be appraised by defining the prevalent hydrochemical facies (Piper, 1944; Back, 1961).

## Hydrochemical Facies

A wide range of water types is present in the South Coastal Plain aquifer (fig. 6). These are related mostly to the mineralogy of the hydrogeologic units. Variation in water type within a given area can be explained by induction of ground water towards wells from aquifer zones containing different water types. In the area west of Río Cañas (stream west of Río Descalabrado), the dominant hydrochemical facies in ground water with less than about 600 mg/L dissolved solids is calcium-bicarbonate. At wells yielding water with dissolved solids concentrations greater than 600 mg/L, the dominant hydrochemical facies are sodium-chloride or calcium-chloride. Analyses from wells yielding sodium-chloride type waters plot in a line trending towards seawater (fig. 7). The wells yielding this type water are in the vicinity of the high dissolved solids concentrations at the western end of the coastal plain (1,000 mg/L contour in fig. 5a) and at Punta Pastillo (600 mg/L contour in fig. 5a). Analyses from wells yielding calcium-chloride type waters plot in a line trending towards the type of waters found at depths greater than 60 m (fig. 7). The wells yielding calcium chloride type water are within the alluvial and associated clastic deposits and underlying carbonates in this part of the aquifer system. Calcium-chloride type waters also occur at wells yielding water from the carbonate units which crop out west of Ponce. At test well SC-5 (fig. 1), a sodium-chloride type water was found within the rubbly limestone unit with a dissolved solids concentration of 2,200 mg/L. The isotopic signature of the water indicated it is of meteoric origin; therefore, the solutes probably originated from the hydrogeologic units.

In the area between Río Cañas and Río Jueyes, the principal variation in hydrochemical facies is from calcium-bicarbonate towards sodium-bicarbonate (fig. 8). Deposits in these areas, possibly derived from geologic units exposed along the foothills, are high in silt and clay and also consist of marine-laid lava and tuff of the Robles Formation, which is rich in albite -- $NaAlSi_3O_8$ --(Glover, 1971). Sodium-bicarbonate type waters occur at depths within the Río Coamo fan, as determined by test drilling at SC-4 (refer to fig. 1 for location) and at the interfluvial part of the Río Descalabrado and Río Jacaguas fans. Unlike sodium-chloride or calcium-chloride type waters, the maximum known dissolved solids concentration of sodium-bicarbonate water in the coastal plain is not greater than 820 mg/L. However, upconing of deep ground water in this part of the aquifer system could affect agricultural enterprises, which depend mostly on ground water as an irrigation water source. The deeper ground water (generally at depths greater than 45 m) has a sodium adsorption ratio (SAR) less than 4.0. This SAR value is considered a low sodium hazard for irrigation purposes, but at wells yielding water with a dissolved solids concentration exceeding 500 mg/L, this water is classified as having a high salinity hazard (U.S. Salinity Laboratory Staff, 1954).

East of Río Jueyes, the predominant water type is calcium-bicarbonate within the alluvial fans of the larger stream basins, and sodium-bicarbonate at the interfluvial areas. Calcium-chloride type water was found below a depth of 80 m in ground water having a dissolved solids concentration of 7,000 mg/L at test well SC-2 (refer to fig. 1 for location) and at a well near the foothills to the west of Salinas. This type of water is possibly related to deep ground-water circulation through marine limestones of Tertiary age. The limestones crop out to the west and

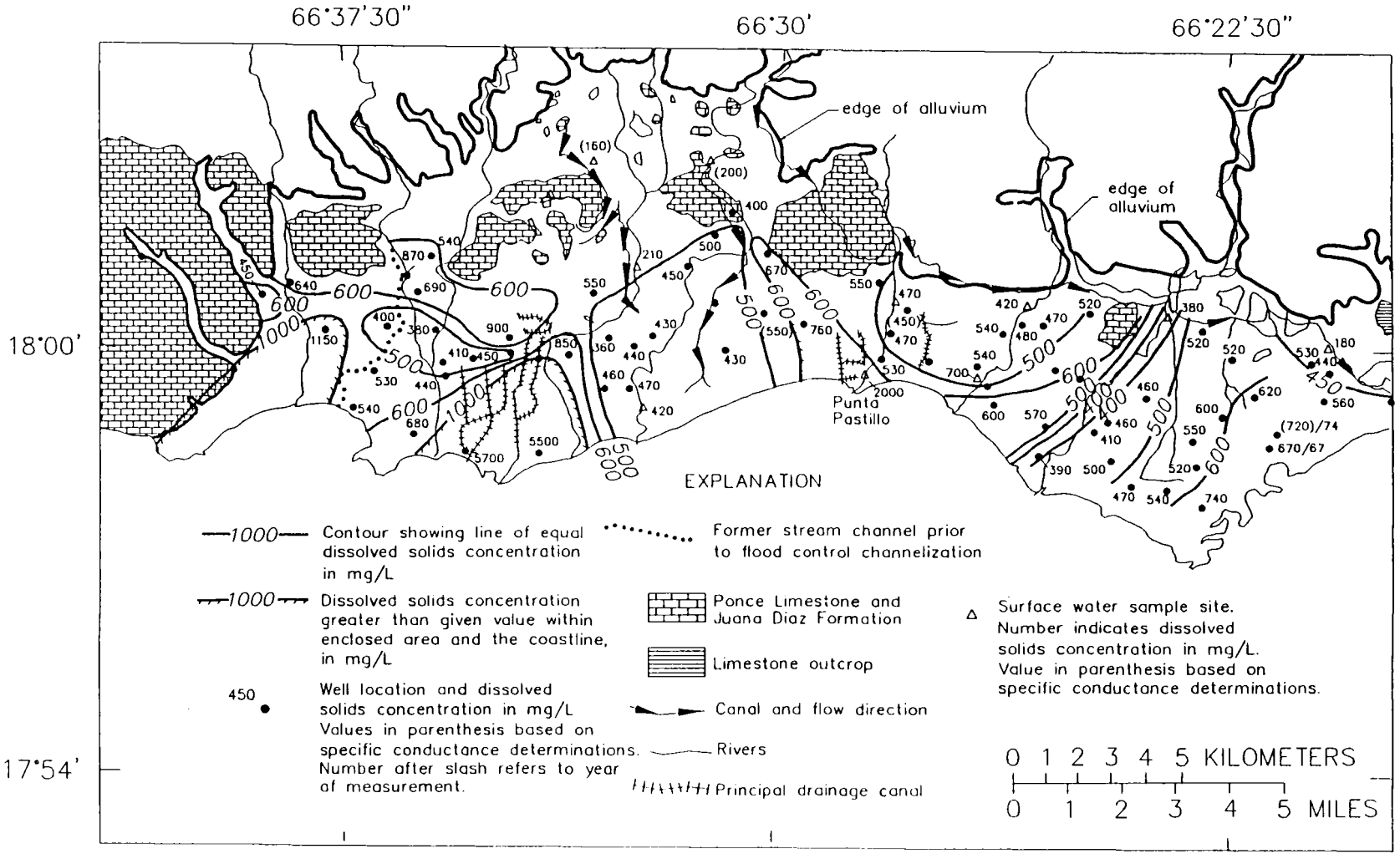



Figure 5(a).--Dissolved solids distribution in the aquifer system in the area west of Río Jueyes.

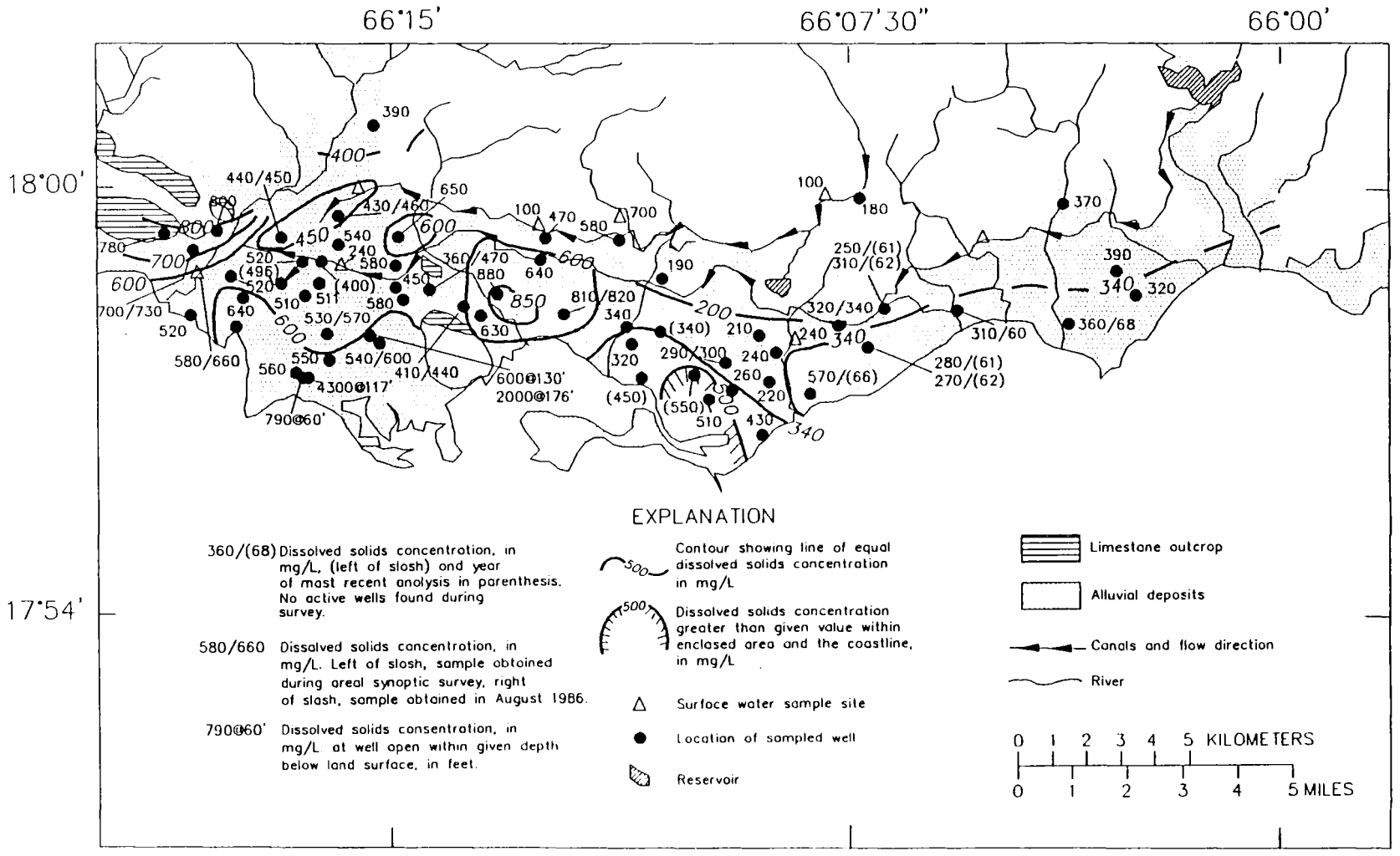
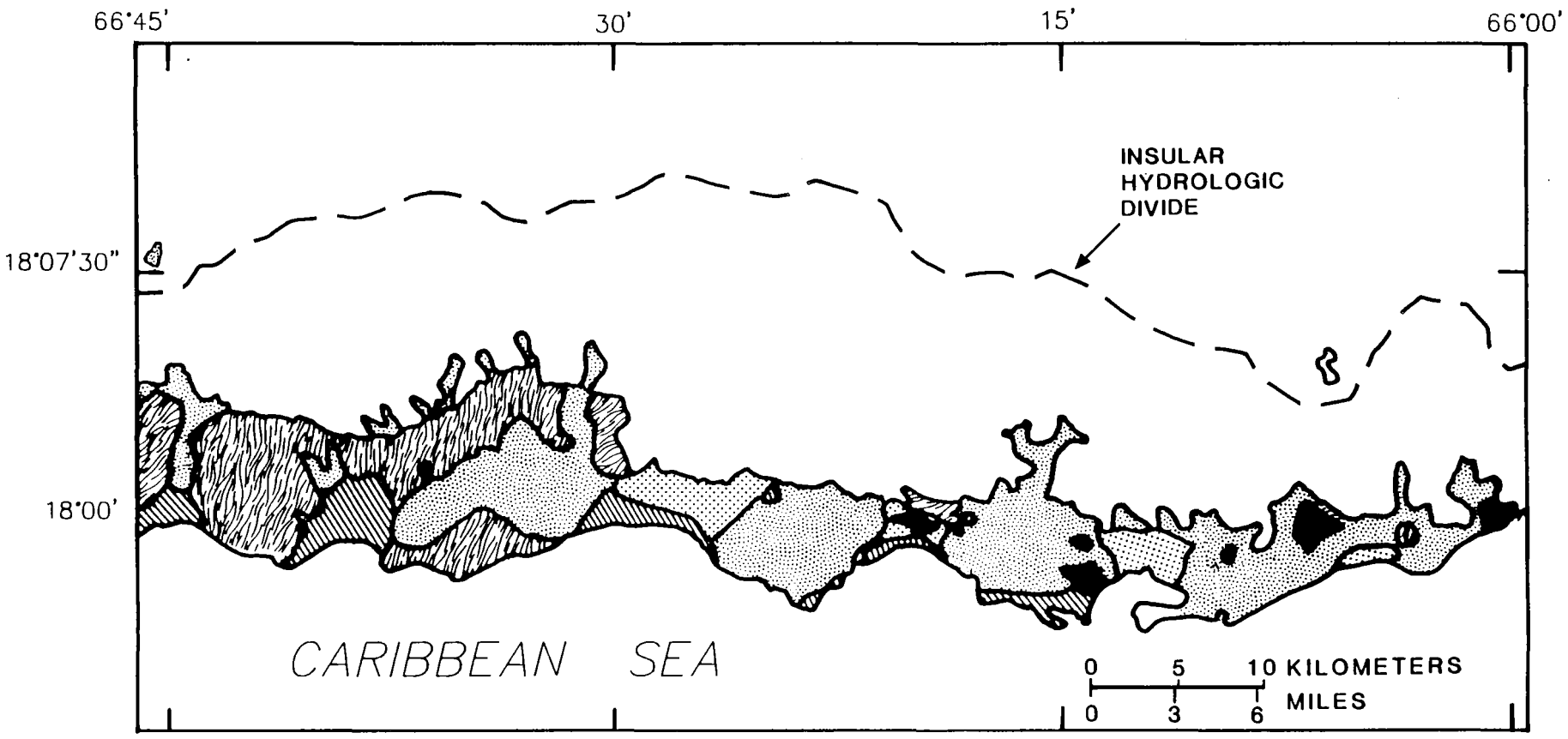



Figure 5(b).--Dissolved solids distribution in the aquifer system in the area east of Río Jueyes.




EXPLANATION

Prevalent water type in wells completed at depth of less than 45 meters

- Calcium-chloride
- Sodium-chloride
- Calcium-bicarbonate
- Sodium-bicarbonate
- Area not defined
- Volcanic rock outcrop

Figure 6.--Hydrochemical facies of ground water.

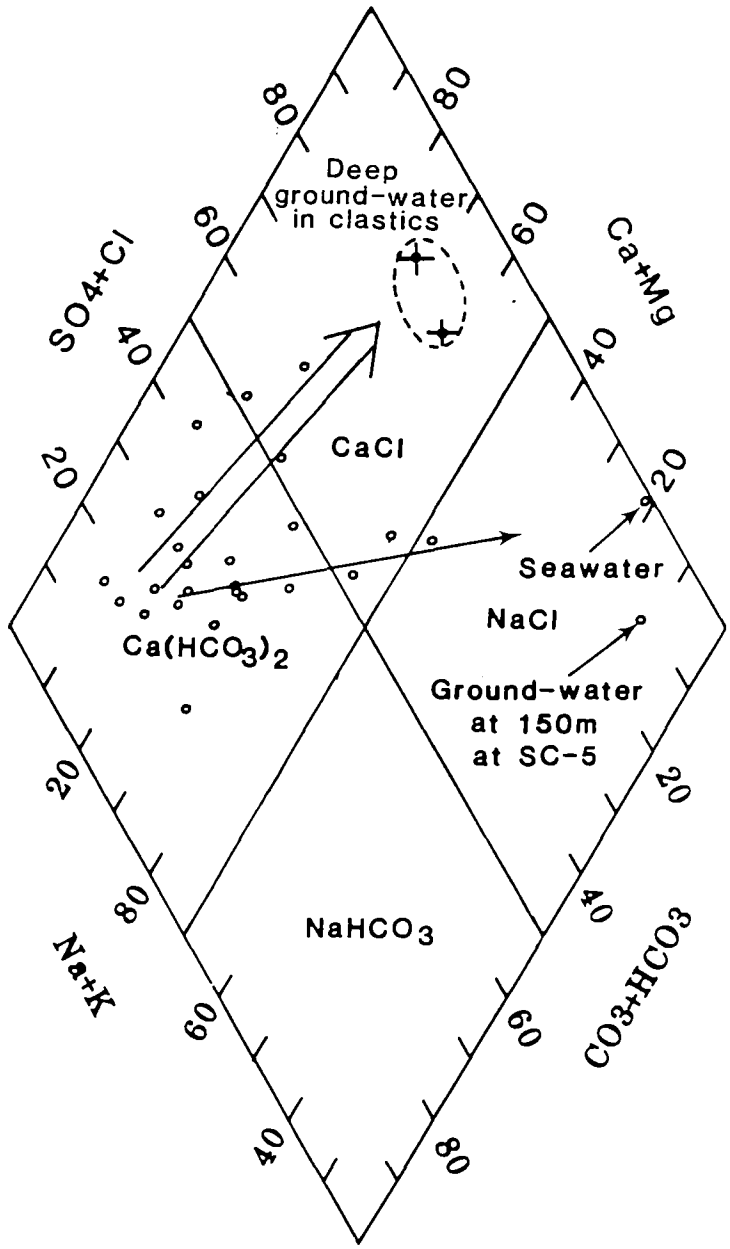



Figure 7.--Trilinear diagram of water chemistry from ground-water samples obtained at wells in the Ponce area. (Arrow indicates tendency of analysis from water well samples, influenced by locations within alluvial fan, total depth of well and pumpage).

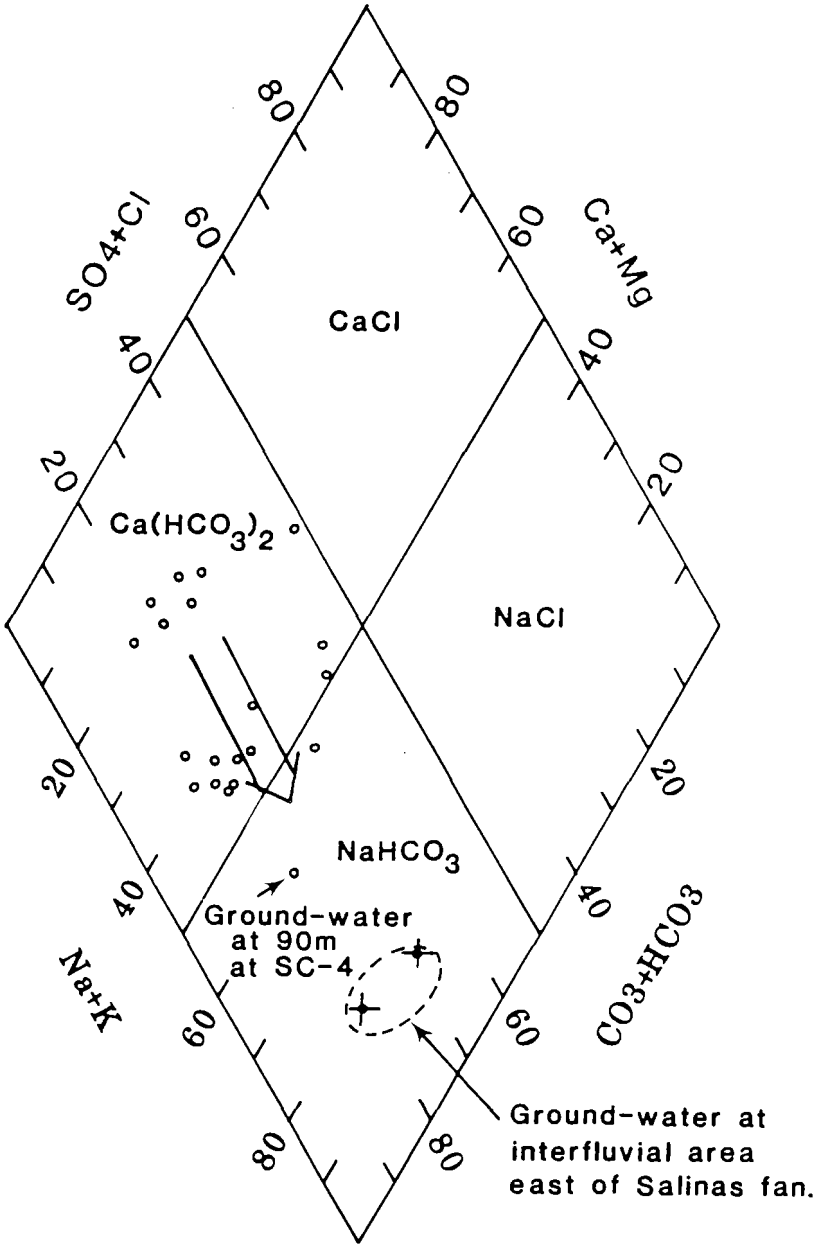



Figure 8.--Trilinear diagram of water chemistry from ground-water samples obtained at wells in the Río Cañas to Río Jueyes area. (Arrow indicates tendency of analysis from water well samples, influenced by locations within alluvial fan, total depth of well and pumpage).

southeast of the Salinas fan and could exist at depth beneath the alluvium. Further east, near Arroyo, a saline water spring (Baños de Virella) also yields a calcium-chloride type water with a dissolved solids concentration of 4,200 mg/L and a temperature of 34°C (ambient ground-water temperature is 28°C). Salt-water encroachment has been reported only within the south-eastern part of the Salinas fan.

## ANTICIPATED GROUND-WATER QUALITY CHANGES

Hydrologic modifications affecting the water balance in the South Coastal Plain aquifer system may, in time, lead to changes in ground-water quality. The anticipated changes are likely to be related to regional upward migration of lower quality ground water. This may be a result of a reduction in aquifer recharge associated with the diversion of streamflow or increases in consumptive ground-water withdrawals. In the area west of Río Cañas, degradation in ground-water quality, as indicated by elevated dissolved solids concentrations, has occurred in some areas (fig. 5a). Streams in these areas have been channelized for flood control purposes, which may have resulted in a reduction of lateral seepage from these streams to the aquifer. Interpretation of the stable isotope composition of ground water in the area indicates a general reduction of the relative proportion of surface-water-derived aquifer recharge toward the west (refer to fig. 4a). Continued ground-water withdrawals and a reduction in streamflow recharge may cause water from wells located near the delineated hydrochemical boundaries to change in composition. Those wells yielding a calcium-bicarbonate type water may, in time, yield a calcium-chloride type water, and those yielding a calcium-chloride type water may eventually yield a sodium-chloride type water. The rate of change is unknown, but could be accelerated if a major drought such as that which affected the island in the mid 1960's recurs.

In areas east of Río Cañas, the major changes in ground-water quality can be expected at the Río Coamo and Salinas fans. In both areas the use of surface water from irrigation canals has been reduced significantly. However, this is expected to have the greatest effect in the eastern part of the Salinas fan where consumptive ground-water withdrawals are large. Seawater encroachment is occurring in the part of the fan along the coast, and upward migration of lower quality calcium-chloride type ground water could be occurring at wells within the eastern part of the fan where the fan overlies carbonate rocks. In the Río Coamo fan, the dissolved solids concentration of ground water appears to have increased by as much as 200 mg/L in some areas since the mid 1960's. This increase in dissolved solids may be related to the decline in surface-water irrigation from the irrigation canals. Streamflow infiltration is estimated to provide about 80 percent of the aquifer recharge as determined through digital modeling of the aquifer system. In addition, consumptive ground-water withdrawals have not changed significantly in the Río Coamo fan within the past 25 years. If consumptive withdrawals increase from the present rate of about 45,000 $m^3/d$, a change in ground-water quality may occur. The anticipated change probably would be most noticeable in the eastern part of the fan which is the furthest point from the principal recharge source -- Río Coamo. In this area upward migration of sodium-bicarbonate ground water and landward migration of seawater may occur.

## SUMMARY AND CONCLUSIONS

The hydrochemistry of the South Coastal Plain aquifer system in Puerto Rico is influenced to a large degree by the modifications made to the natural flow system. Major modifications to the natural hydrologic conditions were made during the early part of this century, mostly as a result of development of irrigation water supplies. These conditions remained virtually unchanged until 1970. Since 1970 about 18,000 ha of land previously in sugarcane cultivation have been left fallow. This has resulted in large-scale changes in the relation between aquifer recharge and discharge, which may lead to regional changes in the hydrochemistry of the aquifer.

A comprehensive survey was conducted to evaluate the present hydrologic condition with respect to recharge sources and sinks, and the hydrochemistry of the ground water. The water quality data was used to develop maps showing dissolved solids distribution and percent ground-water flow derived from surface water sources. The latter were obtained by establishing the relative signatures of the stable isotopes of deuterium and oxygen-18 for surface water and native ground water. These interpretations were used in conjunction with hydrochemical facies maps and knowledge of the ground-water flow system to determine which aquifer areas are more susceptible to water quality changes as a result of hydrologic modifications.

The results indicate that in the western part of the aquifer system the quality of ground water is currently undergoing a major change. Shallow ground water, which is of a calcium-bicarbonate type, is being replaced by deeper ground water that is higher in dissolved solids and of a calcium-chloride type. This deeper water is meteoric water possibly originating at the upland parts of the alluvial plain where the unconsolidated deposits overlie the carbonate units. This calcium-chloride type of ground water is being replaced by sodium-chloride type water in the extreme western end of the alluvial plain and in the general vicinity of the mouth of Río Jacaguas. These two areas and the southeastern part of the Salinas fan are the only sites where seawater encroachment is apparent.

Other areas where a change in ground-water quality is anticipated are the Río Coamo and the Salinas fans. The use of surface water for irrigation on the fans has decreased significantly. In the Río Coamo fan the principal source of aquifer recharge originates from streamflow infiltration. Although no major change in ground-water quality in this area has occurred, consumptive ground-water withdrawals at or in excess of the present rate, may lead to a deterioration in ground-water quality as a result of upconing of deeper sodium-bicarbonate type water and seawater encroachment along the coast. These changes in ground-water quality are likely to be most noticeable in the southeastern part of the fan which is the area farthest from the surface-water recharge.

At the Salinas fan, it is possible that a significant change in ground-water quality will occur in the southeastem part of the aquifer. The aquifer in this part of the fan is almost totally dependent on recharge derived from irrigation canals to sustain the existing ground-water withdrawals. Continued ground-water withdrawals and reduced surface-water recharge may lead to upconing of deeper calcium-chloride type ground water and further seawater encroachment in the southeastem part of the fan.

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