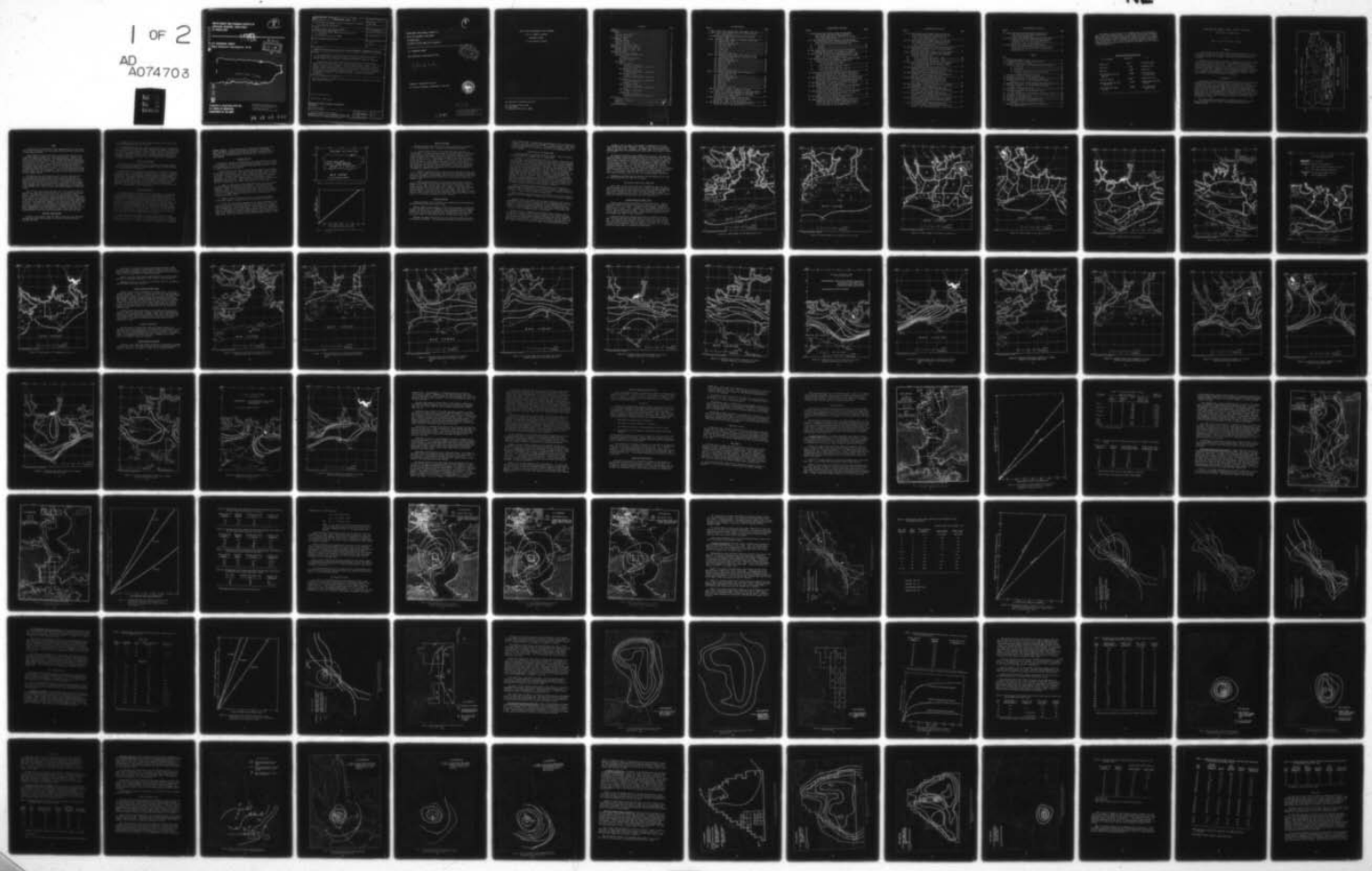
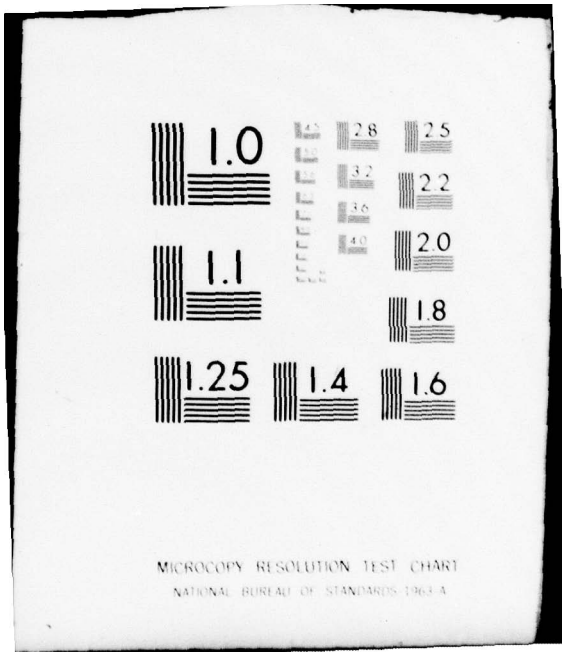
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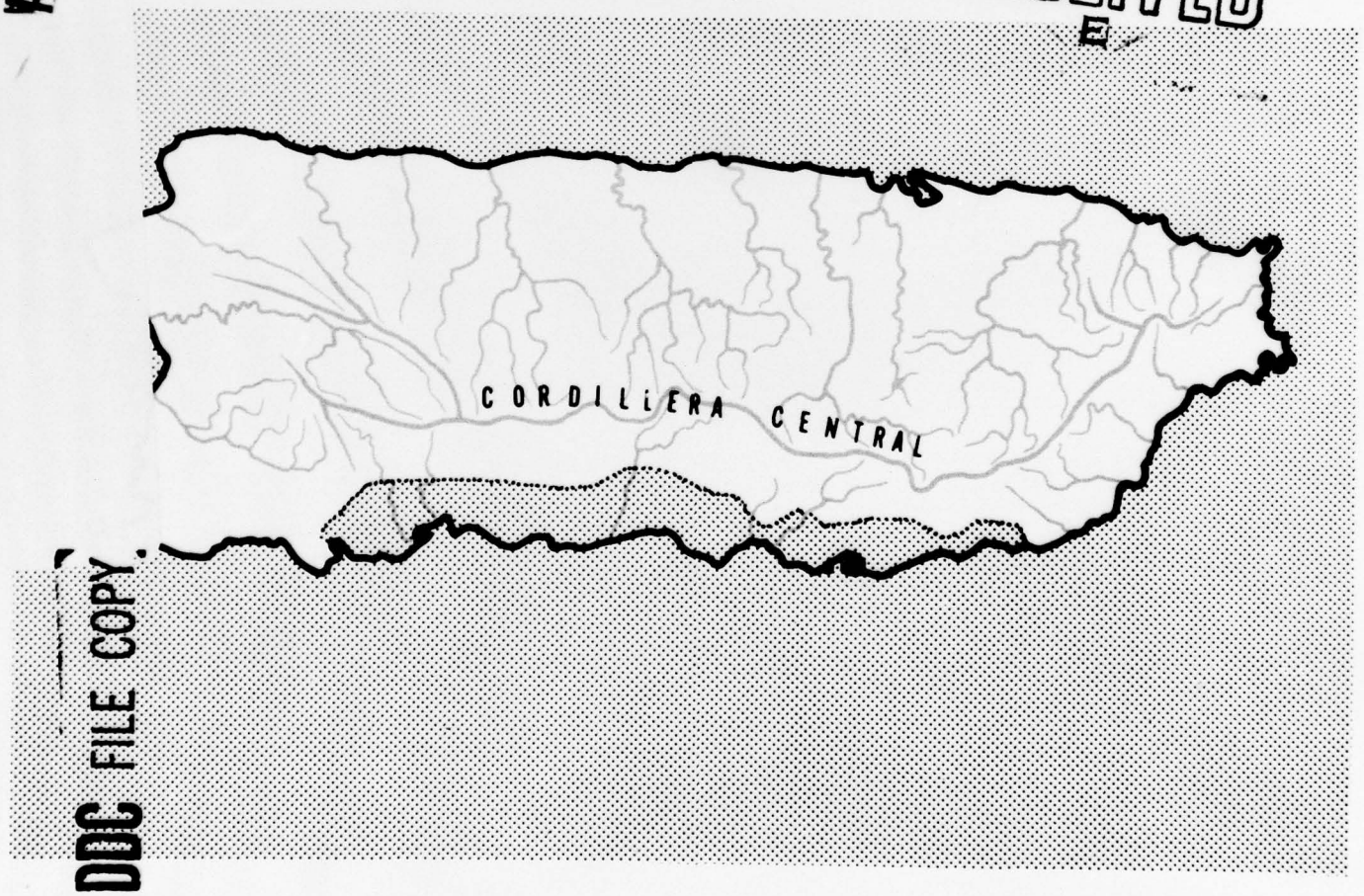
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This report is written using U.S. customary units for all distances, areas, flows, and loading factors. For those who are more familiar with or have a need to use SI units (International System) this table is included. The table contains a conversion factor with which to multiply the customary unit to yield the SI unit. Conversion factors are shown to 4 significant figures but units in the text are rounded to be consistent with the accuracy of the customary unit.

Table of Units and Conversions

U.S. customary	Conversion	SI
inches (in)	25.40	millimeters (mm)
miles (mi)	1.609	kilometers (km)
feet (ft)	.3048	meters (m)
million gallons per day (Mgal/d)	.04381	cubic meters per second (m^3/s)
acres per Mgal/d	9.238	hectares per m^3/s
gallons per day per foot [(gal/d)/ft]	.01242	meters squared per day (m^2/d)
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)

WATER BUDGET AND HYDRAULIC ASPECTS OF ARTIFICIAL RECHARGE, SOUTH COAST OF PUERTO RICO

by

James E. Heisel and José R. González

ABSTRACT

An analog model was used to evaluate ground-water conditions on the south coast of Puerto Rico. Water levels during a normal period and during an extended drought were simulated. Recharge and discharge values are reported.

The model was also used to evaluate the possibilities of using treated waste water to recharge the aquifer. Three methods were considered: infiltration basins, injection, and irrigation. The tests were planned to determine what changes in water levels would result if certain rates of application were used. Because of the limited vertical hydraulic conductivity, irrigation is suggested as the most practical method of waste water use. Injection, though practical from the mechanical standpoint, may be objectionable from health and aesthetic standpoints.

INTRODUCTION

This report summarizes the findings and activities of an investigation whose overall purpose was to evaluate the ground-water conditions in selected areas (fig. 1) on the south coast of Puerto Rico. An analog model was used to evaluate the water budget and ground-water levels during a normal period and also under a drought condition which approximated the period from 1971 to 1973. The model was also used to evaluate the change in water levels that can be expected if treated waste water is returned to the aquifer utilizing infiltration basins, irrigation, or injection wells, and to determine if water reuse is a possible solution to the chronic water shortage in this area.

This investigation was performed in cooperation with the U.S. Army Corps of Engineers as part of their Ponce Regional Water Resources Management Study.

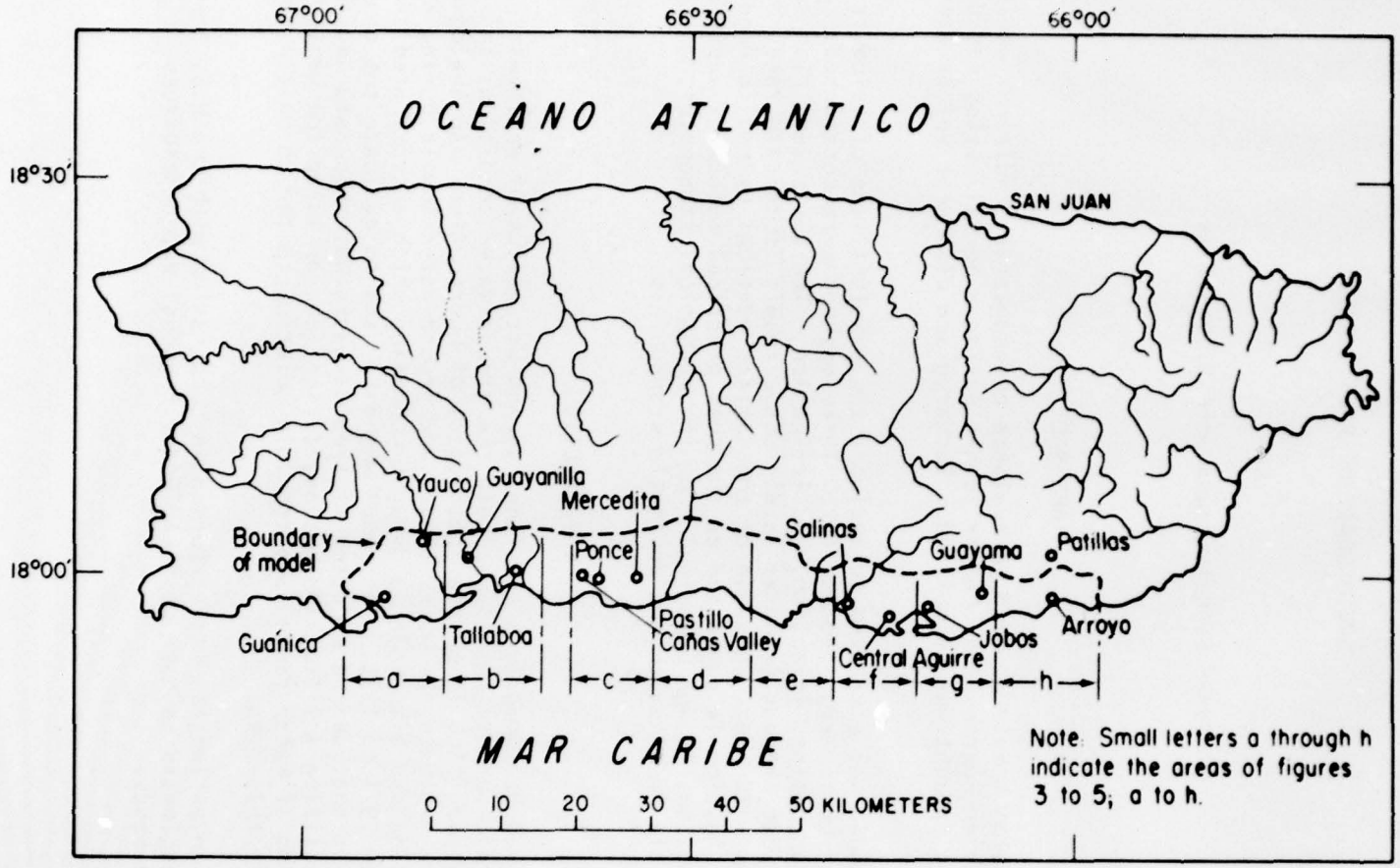


Figure 1.--South Coast Model Study Area

Area

The south coast of Puerto Rico is dry compared to most of the island. Most of the rain occurs in the late summer and fall and very little occurs in the winter and spring.

Precipitation on the alluvial plain varies from an average of 33 in a year near Guánica to about 44 in near Central Aguirre. Rainfall also varies in a north-south direction. The orographic effect and prevailing wind directions are such that the coast is drier and rainfall increases in the direction of the foothills. In the coastal plains the average rainfall is less than 40 in a year. Streams that enter the coastal plain drain mountainous areas where bedrock is close to the surface and rainfall is considerably higher--80 to 90 in per year. In spite of this, many streams in the plains are dry most of the year. Water in the streams draining the mountains soaks into the streambed soon after reaching the plains, providing much needed recharge.

The major aquifers and the ones of concern in this report are the alluvial fans that form the coastal plains. From Ponce eastward to Patillas these fans coalesce to form the continuous coastal plain that is about 43 mi long and from 0.9 to 4 mi wide. In the western part of the study area the alluvium is discontinuous, occurring only in the drainage valleys between large limestone hills. The limestone hills are generally of low permeability in their core but have greater permeability along their flanks.

East of Ponce, water-table conditions occur in the bedrock foothills north of the study area and for the most part, on the upper coastal plain. However, discharge areas along the coast are identifiable by swamps, mangrove areas, and a high water table and artesian pressures in deep wells. This is due to the occurrence of coarser-grained materials near the bottom of the aquifer and finer-grained material at the top, creating semiartesian conditions. More water moves seaward in the lower part of the aquifer than at the top. The condition is important to the ground-water user on the south coast, because it provides a measure of protection against water-quality degradation due to encroachment of saltwater from the sea. In many areas, pumping-water levels are below sea level inland, while artesian pressures above or near sea level may be found in wells near the coast.

Previous Investigations

Studies of the specific areas that make up the south coast have been performed and reports are available in the form of Puerto Rico Water Resources Bulletins.

The areas are outlined in figure 2 and the reports are listed in the selected references section of this report.

An analog model of the south coast alluvial aquifer was constructed by the U.S. Geological Survey analog model laboratory at Phoenix, Arizona under the direction of Gordon Bennett. Bennett (1976) reported on the model which was built using data obtained in earlier studies. Certain modifications were made on the model for this study. These modifications were made only to boundary conditions and values, and not to the hydraulic conductivity simulated in the model.

Goals of the Project

The primary goal of the project was to identify water-budget boundary values using the analog model to simulate water levels in a normal period and in an exceptionally dry period.

Another goal was to evaluate the possibility of recharging the aquifer using waste water. The Commonwealth of Puerto Rico is involved in planning and building three regional sewage treatment plants at Ponce, Guayanilla, and Guayama. It has been suggested that the effluent from these plants be reused. This study makes use of the analog model to determine: (1) what water-level changes would occur if certain amounts of treated water were applied to the land by irrigation, injection, and infiltration basin techniques; and (2) whether the aquifer could accept and redistribute this water if it were applied by any of these means.

GROUND-WATER REGIME

For several centuries, surface water has been used for irrigation on the south coastal plain of Puerto Rico. A stress undoubtedly was applied to the alluvial aquifers as recharge from the water-spreading effect of irrigation. The irrigation system based on surface water reached its peak in the 1940's. Prior to 1940, ground-water pumpage from the alluvial aquifers was slight--being primarily industrial, associated with sugarcane refining, or for small municipal supplies. Between 1940 and 1960 a new ground-water regime was imposed on the old with the development of ground water for irrigation. Irrigation with ground water not only supplemented the surface water used for irrigation but in some areas replaced it. Thus a new ground-water regime was developed with new stresses due to pumpage and a reduction in recharge from surface-water sources.

In the 1960's, the development of industry with large water demands created new stresses and with them a new ground-water regime. In some areas irrigated sugarcane land was taken out of production by industrial development. Depending upon the industry, an increase or reduction in ground-water

pumpage resulted. If the land had been irrigated by surface water, a net loss in recharge, at least locally, usually took place. The general impact was one of diminishing recharge from the water-spreading effect of irrigation and increasing stress on the aquifer due to increased ground-water pumpage.

Recharge Sources

The alluvial aquifers are replenished by (1) water falling on the land as precipitation, (2) water infiltrating from the streams, (3) water running off the bedrock hills and infiltrating the alluvium, and (4) excess irrigation water seeping into the aquifer.

1. Water falling on the land as precipitation provides little recharge during most rainfall events. Only when a large storm dumps several inches on the area in a relatively short time is there sufficient water to recharge the aquifer. Different areas will receive different amounts of recharge, some none, from this source. However, this is not the major source of recharge on the south coast. Most of the rain is utilized in replacing soil moisture of which there is a chronic deficiency on the south coast.

2. Water infiltrating from the streams where they cross the alluvial aquifers provides some recharge to the aquifers. The effect of their recharge is local, its benefit being greatest right at the stream and diminishing rapidly at a distance from the stream. Most of the recharge from this source occurs in the higher parts of the alluvial plains near the foothills. In some places and at some times this is the major source of recharge (McClymonds, 1972).

3. Water running off the bedrock hills as sheet flow provides an insignificant amount of recharge to the alluvium along the foothills.

4. Excess irrigation water seeping into the aquifer provides a large amount of recharge to the alluvial aquifers on the south coast. Much of this irrigation water is diverted from the streams soon after they enter the alluviated area; some is ground water. Varying amounts of the applied water are recharged to the aquifer; some estimates for certain areas are given in the literature: Coamo 30 percent (Giusti, 1971); Ponce 19 percent (McClymonds, 1972); and Jobos 30 to 50 percent (McClymonds and Díaz, 1972).

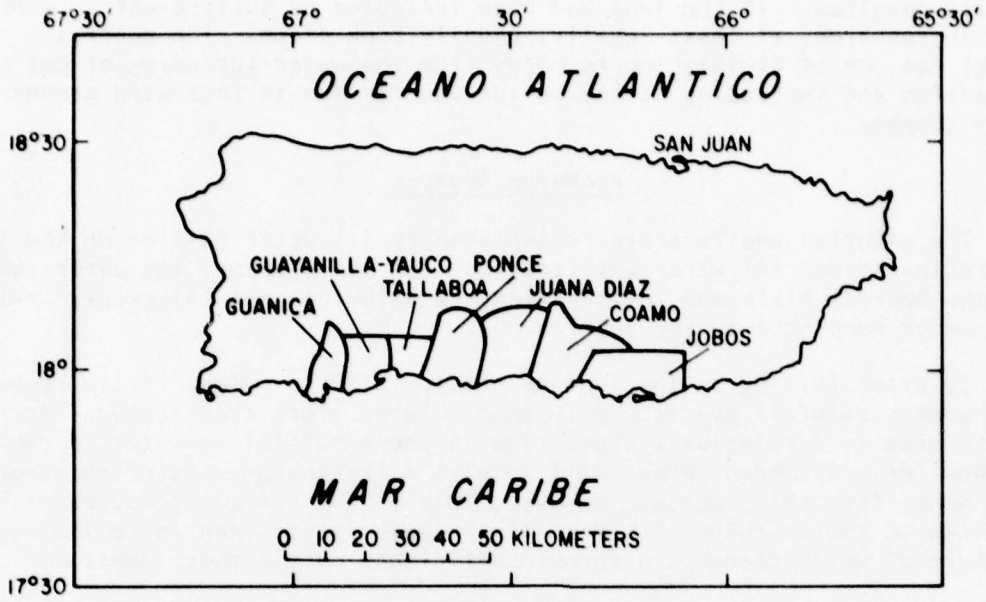


Figure 2.--Location Of Previous South Coast Investigations

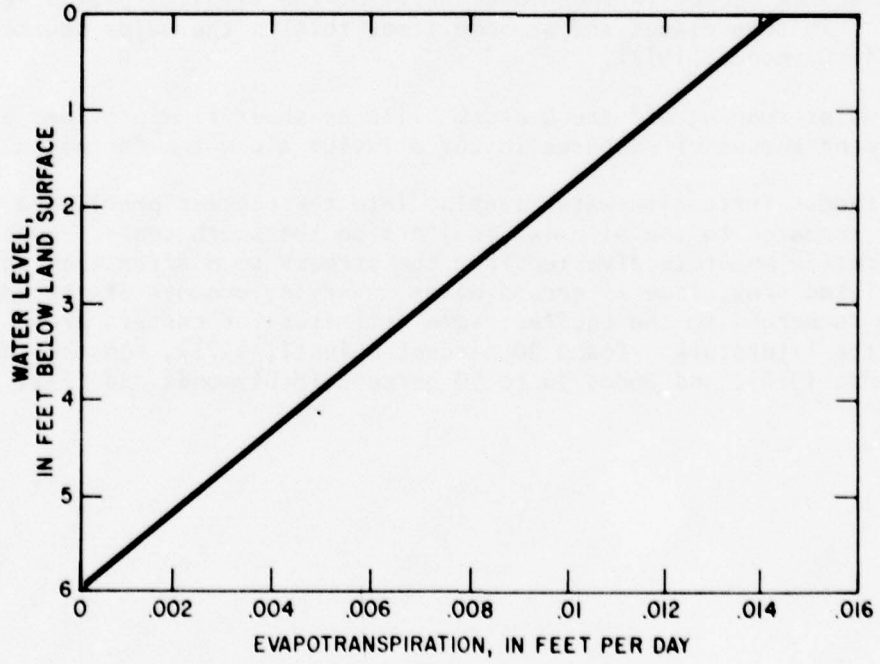


Figure 3.--Average evapotranspiration as related to depth to water.

Natural Discharge

Natural discharge from the alluvial areas consists of (1) surface runoff, (2) ground-water flow to the sea, and (3) evapotranspiration.

1. Surface runoff consists of (a) water that enters the area as surface water, in streams passing through the alluvial area, (b) runoff from precipitation on the alluvial plain, and (c) water that emerges from the ground and enters the streams and canals as base flow. During the wet season, streams may carry large amounts of water as they enter the coastal plain from the foothills; some of this is carried across the coastal plain to the sea where its usefulness as freshwater is lost. During the dry season most of the stream channels in the alluvium will be dry, except near the coast where the bottom of the stream channel is below the water table. The stream will then become a gaining stream as water from the aquifer is discharged as ground-water runoff.

2. Offshore ground-water flow to the sea occurs along most of the south coast. Locally, under heavy pumping conditions, this flow may be temporarily reversed. The amount of ground water lost to the sea for the area from Ponce to Patillas was determined to be 10 Mgal/d for a period with little rain (Bennett, 1976).

3. Direct evapotranspiration from the water table affects the water budget of the aquifer only near the coast where the water table is near the ground surface. Away from the coast, soil moisture is involved in this process but not water from the water table. About 5 in per month evaporates from the aquifer if the water table is at the surface. This value is reduced relative to the distance from the water table to the land surface so that at a depth of about 6 ft no more evaporation takes place (Bennett, 1976). Figure 3 is a graphical presentation of this relation.

Induced Discharge

Induced discharge from the aquifer is by pumping wells and ground-water discharge through the coastal canal system.

Bennett (1976) reported pumpage from the alluvial aquifer of 148 Mgal/d of which 134 Mgal/d was for irrigation in the area between Ponce and Guayama. Pumpage data are the sum of withdrawals from 46 subareas within the larger area for the period between 1961 and 1969. Monthly values were determined for a year in each of the subareas but not the same year in each case.

Wetlands and swamps that parallel the coast have been drained and the land used for agriculture. The drainage has required an extensive network of

closely spaced canals. The wetlands and swamps were areas of ground-water discharge. The canal system has permanently lowered the water table and has probably redistributed the pattern of ground-water discharge, causing less to be discharged directly to the sea, and more to be discharged in the former wetlands.

DESCRIPTION OF THE ANALOG MODEL

The analog model was described by Bennett (1976). Some of the basic design parameters are repeated here for convenience.

The model is a three-dimensional electrical network. There are three vertical layers, each of which simulates a depth zone in the saturated part of the aquifer. All these zones have a horizontal nodal spacing of 800 ft in both the north-south and east-west directions. The top layer represents the top 30 ft of the saturated part of the aquifer; the second layer represents the 70-ft saturated zone between -30 and -100 ft; and the last zone represents all of the saturated zone in excess of 100 ft. The deepest saturated zone extends to 300 ft but is adjusted to simulate accurately the proper depth in areas where the total thickness is less than 300 ft but greater than 100 ft. The third layer is not modeled where the saturated thickness is less than 100 ft. Similarly, the second layer is adjusted to simulate accurately depth between 100 and 30 ft and is not modeled in areas where the saturated thickness is less than 30 ft. Recharge is applied to the model in the top layer only and in alternate nodes of alternate rows. The spacing between consecutive recharge nodes is 1,600 ft.

Vertical connection between the modeled zones is also simulated at alternate nodes in alternate rows. The vertical hydraulic conductivity is modeled so that $K_V = 0.001\ K_H$, where K_V is the vertical hydraulic conductivity and K_H is the horizontal hydraulic conductivity.

Where rivers play an active part in the analysis, the vertical hydraulic conductivity of the riverbed is assumed to be 0.1 of the horizontal conductivity.

Boundary flows on the streams were simulated through resistors chosen as representative of the vertical conductivity of the streambed material. The free ends of these resistors were grounded for nonsteady-state operation. Boundary inflows are simulated by applying current to affected areas along the alluvium bedrock contact, except in the areas west of Ponce where the limestone bedrock is modeled as part of the aquifer.

Boundary flows are simulated at the seashore and the seaward limit of the aquifer by connecting points along the shore to zero voltage (representing sea level) through resistors chosen to simulated the vertical conductivity of the alluvial material for one-half the thickness of the top layer, and points at the seaward limit to a small positive voltage (representing the head caused by the denser seawater at depth) through appropriate resistors.

Storage in the top layer of the aquifer is modeled as 0.15 in the alluvium and 0.25 in the limestone. Storage is also modeled in alternate nodes of alternate rows. Storage in the deeper zones is also modeled but because these cannot be considered water-table zones, the storage is modeled at 1×10^{-4}.

No separate verification was attempted for this study. The model was tested by Bennett (1976) and seemed to match field data with some variations. Where the analog results did not exactly follow the field data the inability of the model to emulate the field data seemed due to assumptions regarding time and space variables. The model was programmed to change recharge and discharge monthly, while in the actual situation the aquifer received recharge at sporadic intervals. The model was programmed for uniform discharges over areas ranging from 64 to 5,000 acres, whereas in actual practice, wells are essentially point discharges and most of the discharge is through wells. In the present simulation only small parts of the aquifer are exercised at one time, except for the first two water-budget simulations.

Assumptions regarding recharge area and time differences do not limit the local simulations described in this report.

SIMULATION OF WATER-LEVEL CONDITIONS

Water levels in the aquifer were first simulated for what are considered average conditions of precipitation, runoff, recharge, and pumpage based on pumpage obtained from previous studies and long-term average rainfall values. Changes in water levels were then simulated to show the additional stresses that would result in the aquifer under drought, approximating the conditions that existed in the area from 1971-73.

Average Conditions Model Input

Average conditions were simulated on a steady-state basis. Pumping rates were modeled as determined from previous reports, and recharge was modeled at 1 to 2 ft per year. In areas of high withdrawal, recharge was proportionately higher. This is reflected in the simulated results and the original work done by Bennett (1976). Values applied as recharge and pumping are shown on figures 4a through 4h, along with the locations of the water-budget areas used for this simulation.

Evapotranspiration was modeled using resistors located at alternate nodes in those areas where the water level is within 6 ft of the land surface. The value of these resistors was chosen so that the evapotranspiration would follow the relationship in figure 3. The remote ends of these resistors were connected to a constant voltage source, set at a voltage representing a water level, 6 ft below the land surface.

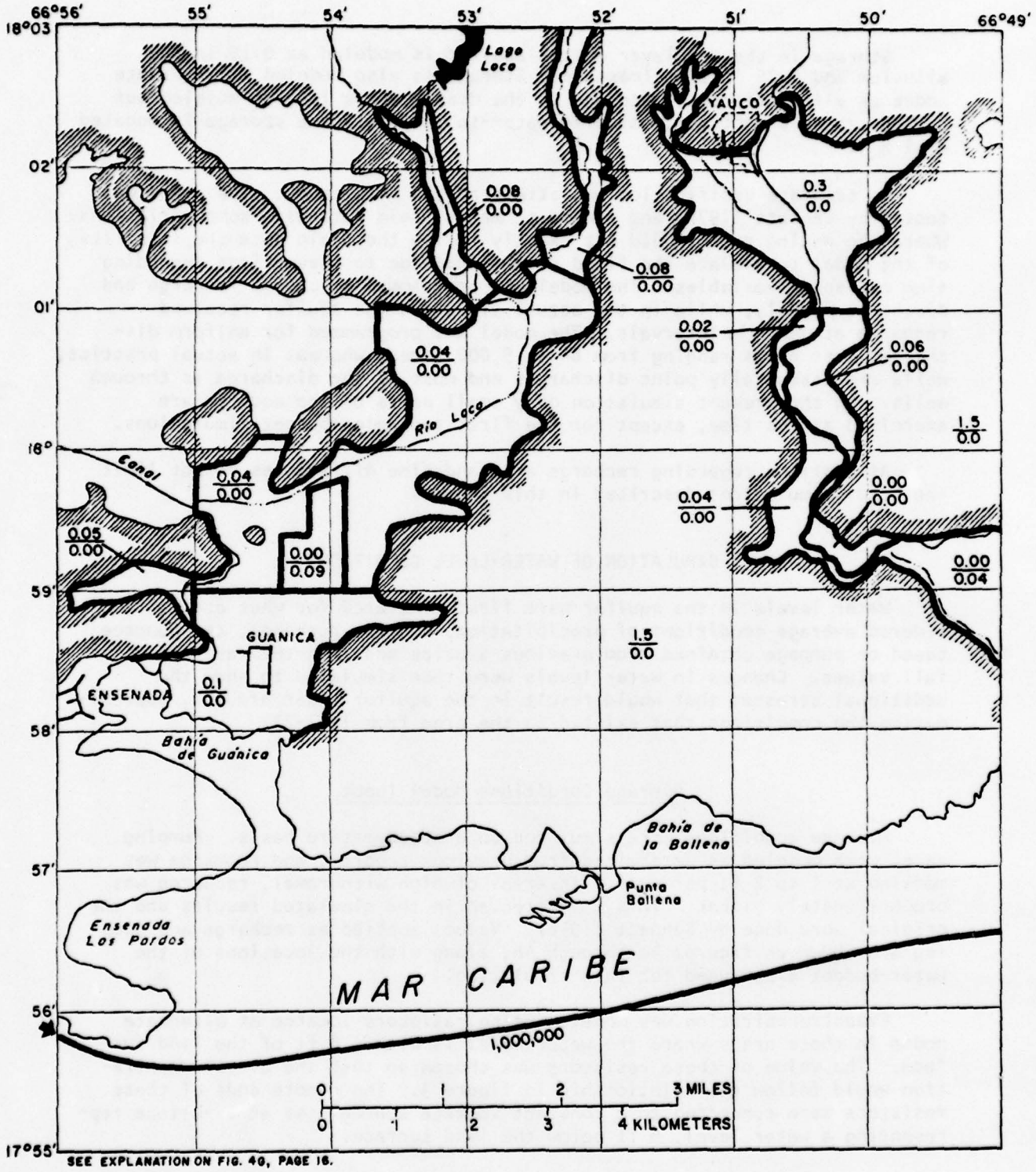


Figure 4a.--Water budget in the Guánica-Yauco area.

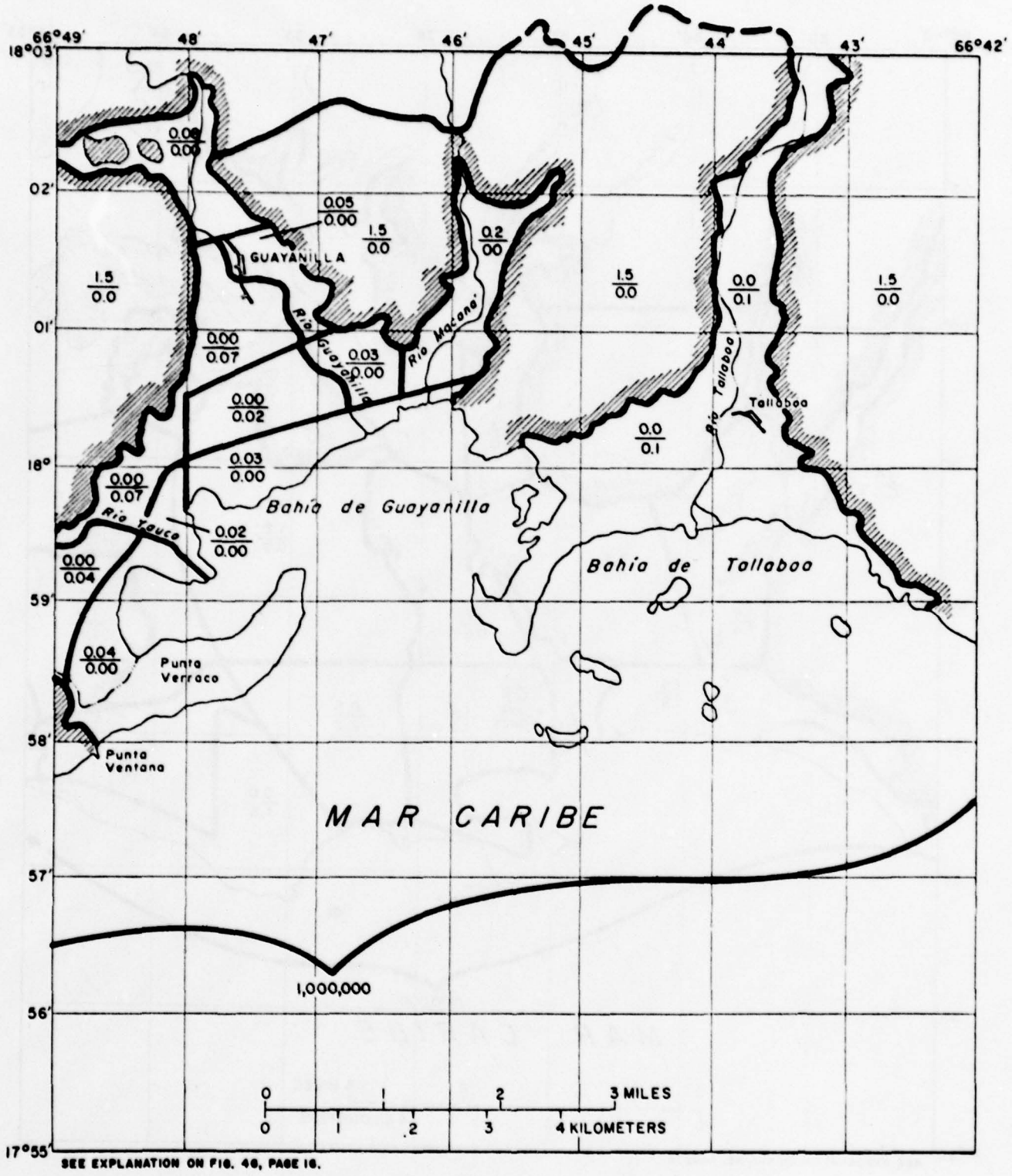


Figure 4b.--Water budget in the Guayanilla-Tallaboa area.

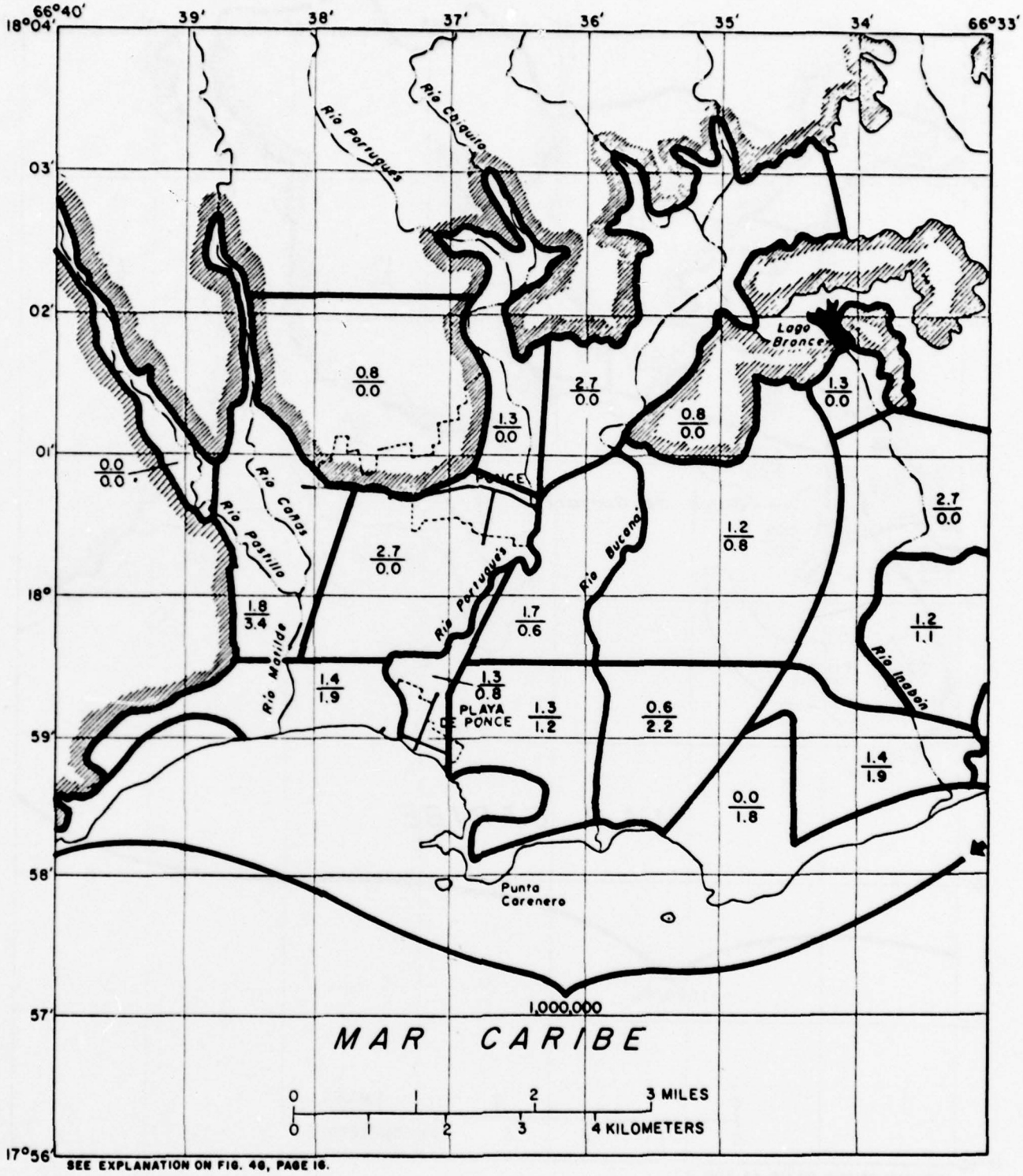


Figure 4c.--Water budget in the Pastillo-Inabón area.

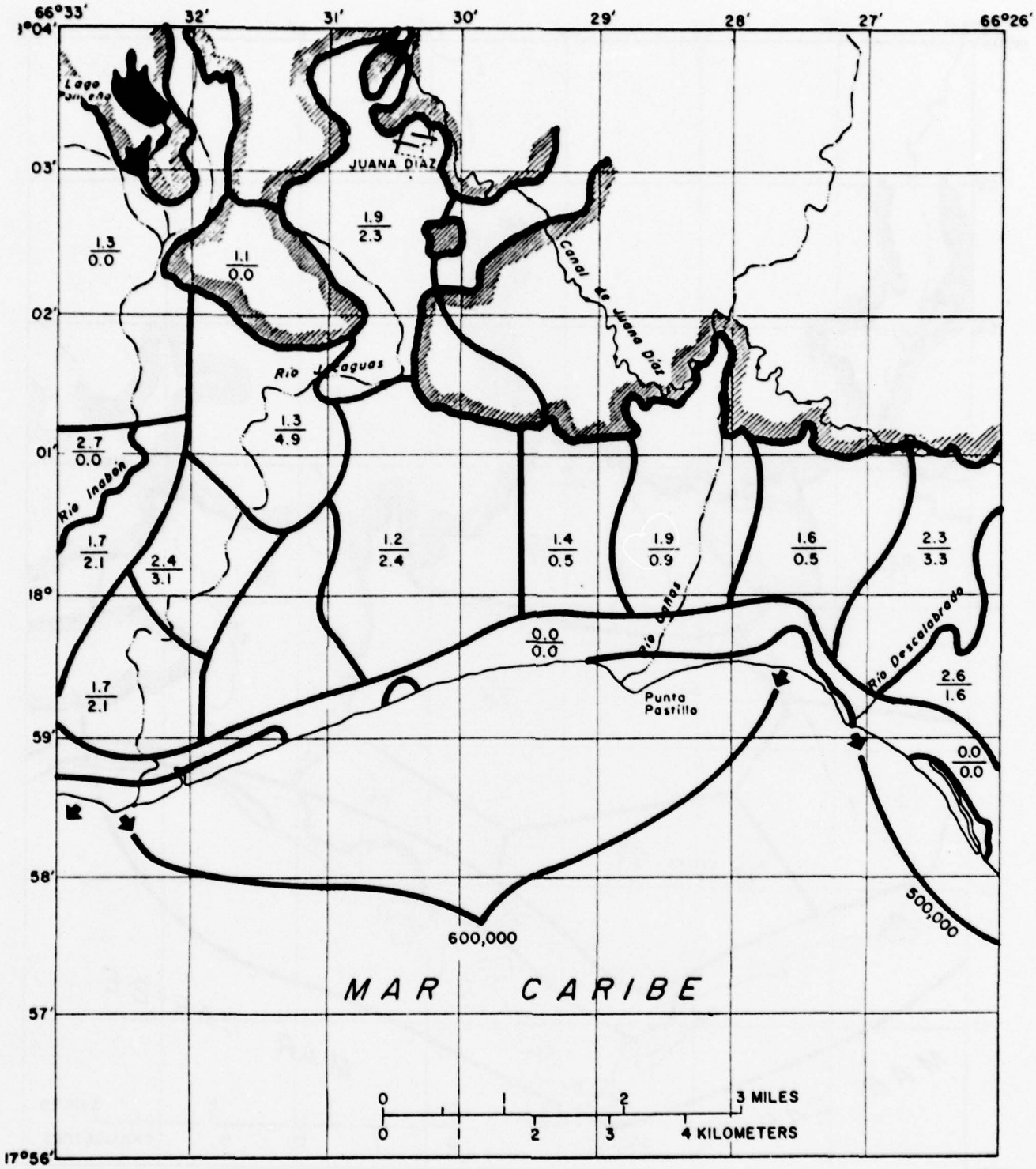


Figure 4d.--Water budget in the Juana Díaz area.

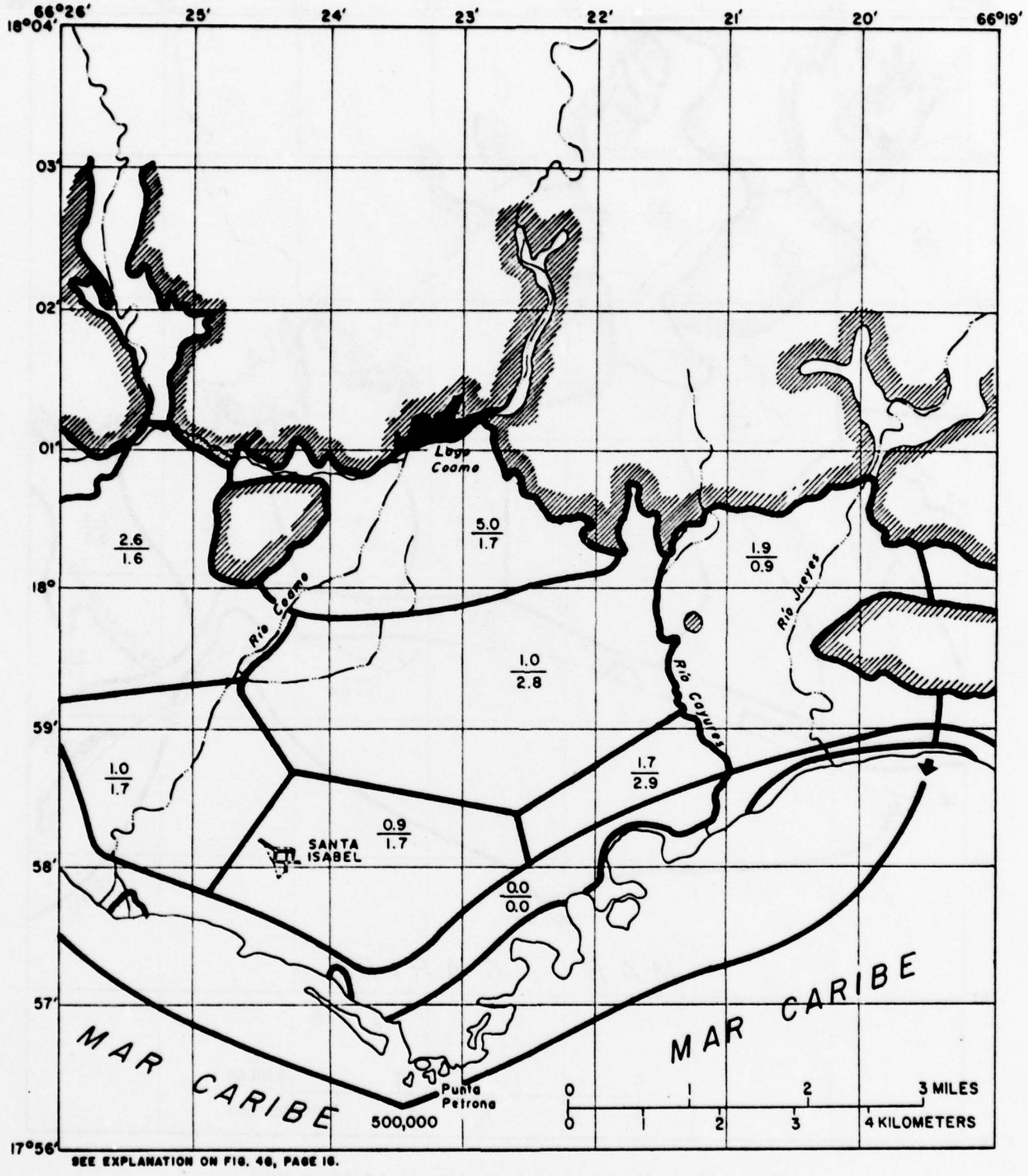


Figure 4e.--Water budget in the Coamo area.

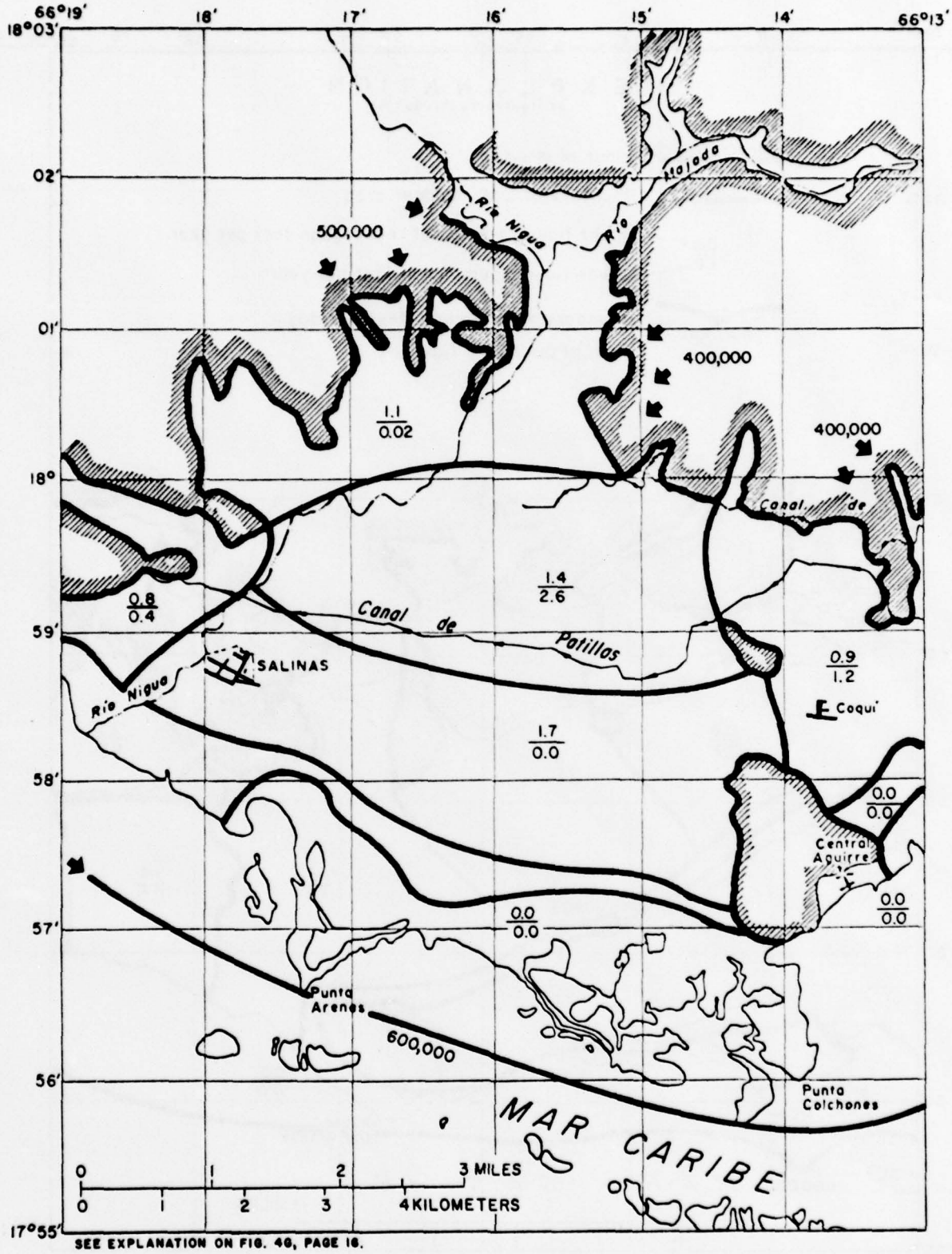


Figure 4f.--Water budget in the Salinas area.

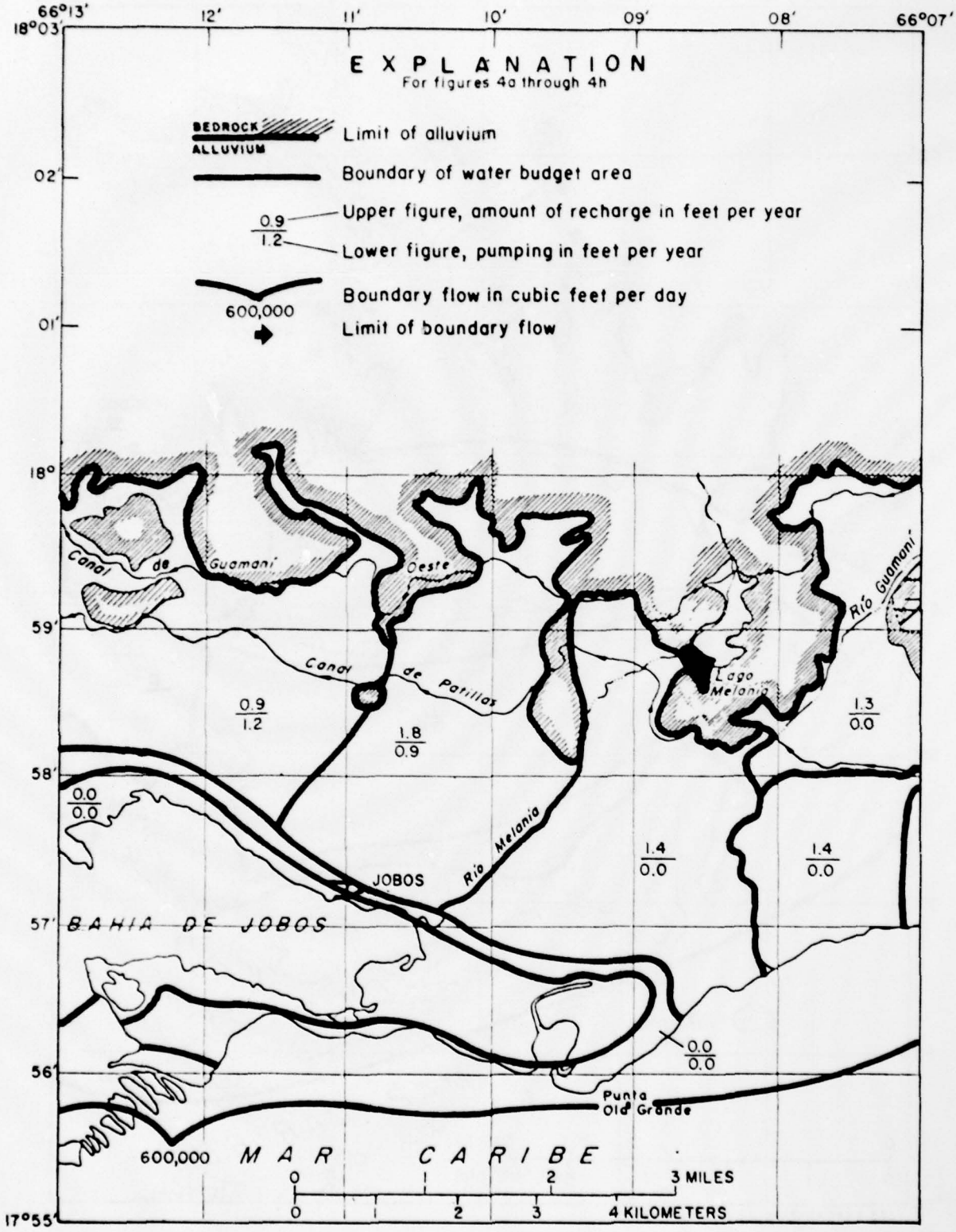


Figure 4g.--Water budget in the Jobos area.

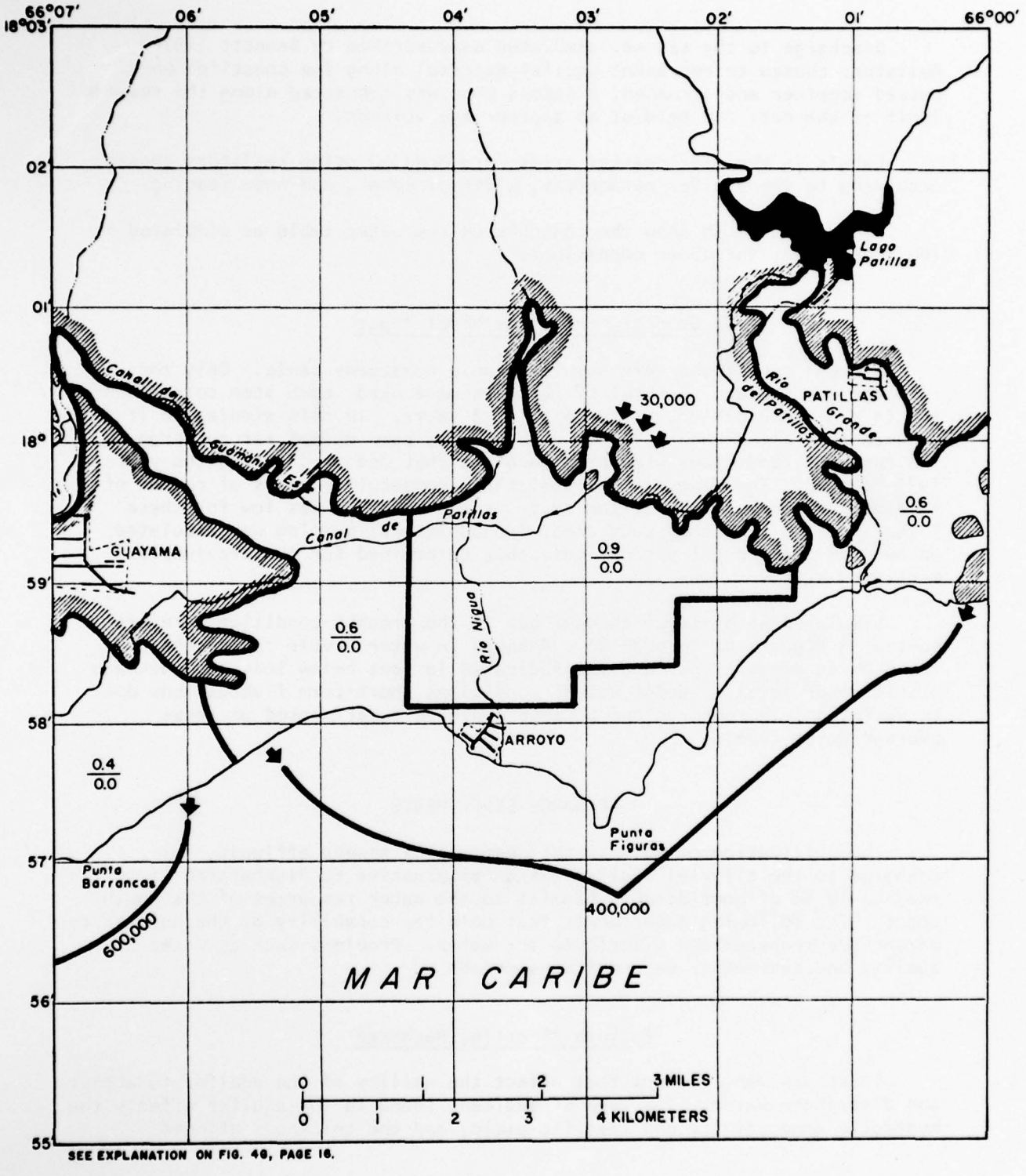


Figure 4h.--Water budget in the Guayama-Patillas area.

Discharge to the sea was simulated as described by Bennett (1976). Resistors chosen to represent aquifer material along the coastline were bussed together and grounded, a second buss was connected along the seaward limit of the net, and held at an appropriate voltage.

Canals in the near coastal areas were modeled using resistors chosen according to the aquifer parameters, width of canal, and node spacing.

Figures 5a to 5h show the contours on the water table as simulated by the model under the above conditions.

Drought Conditions Model Input

Drought conditions were simulated on a nonsteady basis. Only the recharge was varied. A total of 12 steps were used, each step corresponding to a 3-month period, for a total of 3 years. In this simulation it was assumed that all boundary values remained the same except for recharge. The recharge conditions simulated recharge that occurred during the years 1971 to 1973. These were the lowest three consecutive years of record of rainfall on the west end of the study area. Rainfall was low for these 3 years over all of the study area. No additional pumping was simulated because of the drought period; only that determined for the previously mentioned study.

Simulated water-level changes due to the drought conditions are presented in figures 6a through 6h. Changes in water levels represented on the figures are averages and are indicated in feet below long term average static water levels. Under actual conditions short-term fluctuations due to variations in recharge and pumpage would be superimposed on these average water levels.

RECHARGE EXPERIMENTS

The utilization of waste water, especially sewage effluent, for recharge to the alluvial aquifer (as an alternative to discharging it to the sea) could be of considerable benefit to the water resources of the south coast. The following experiments test only the capability of the aquifer to accept the recharge and distribute the water. Problems such as water quality and aesthetics were not considered.

Factors Affecting Recharge

There are many factors that affect the ability of the aquifer to accept and distribute water. The type of sediment found in the aquifer affects the hydraulic conductivity and specific yield, and the thickness affects

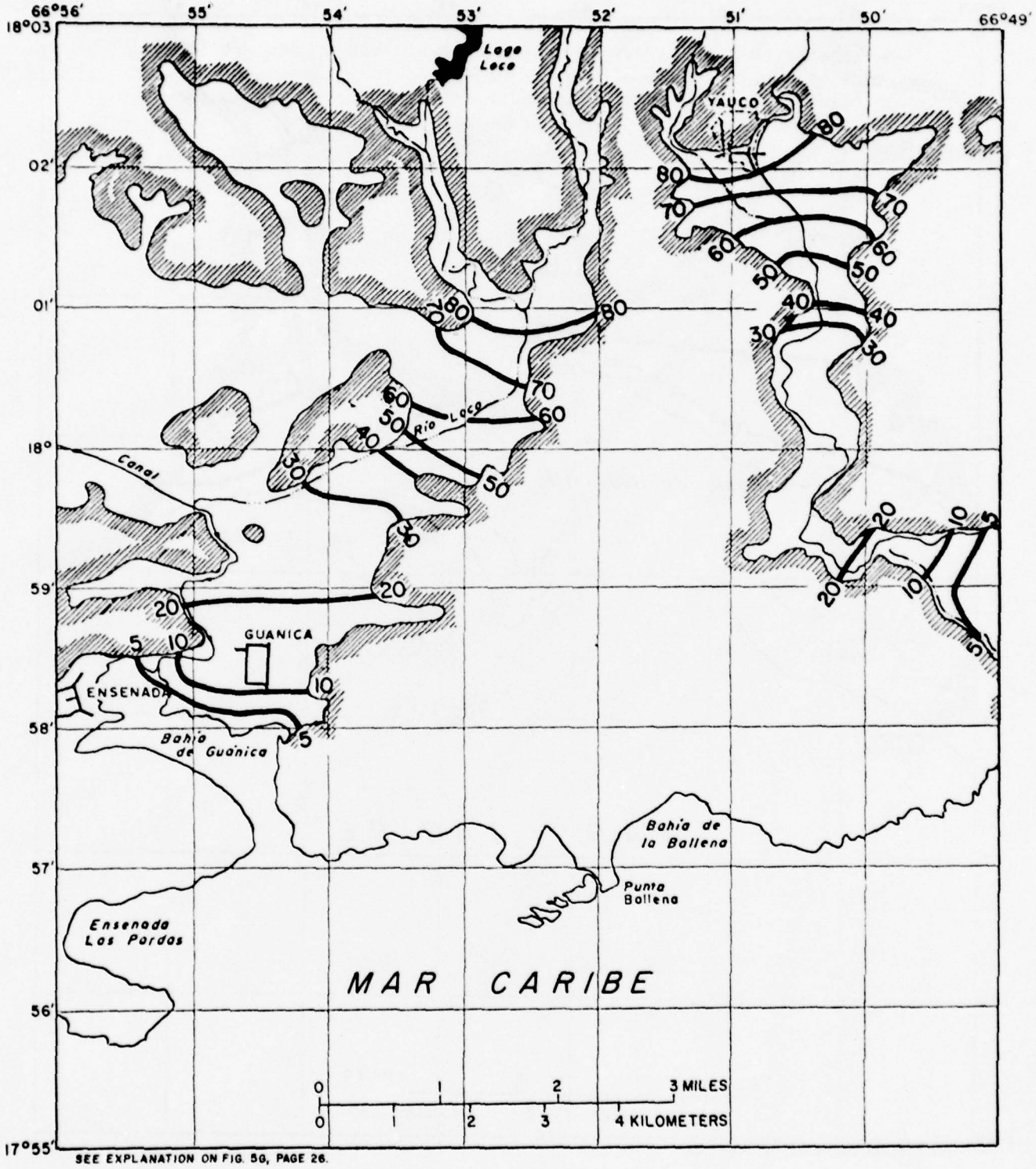


Figure 5a.--Simulated water levels resulting from average boundary conditions in the Guánica-Yauco area.

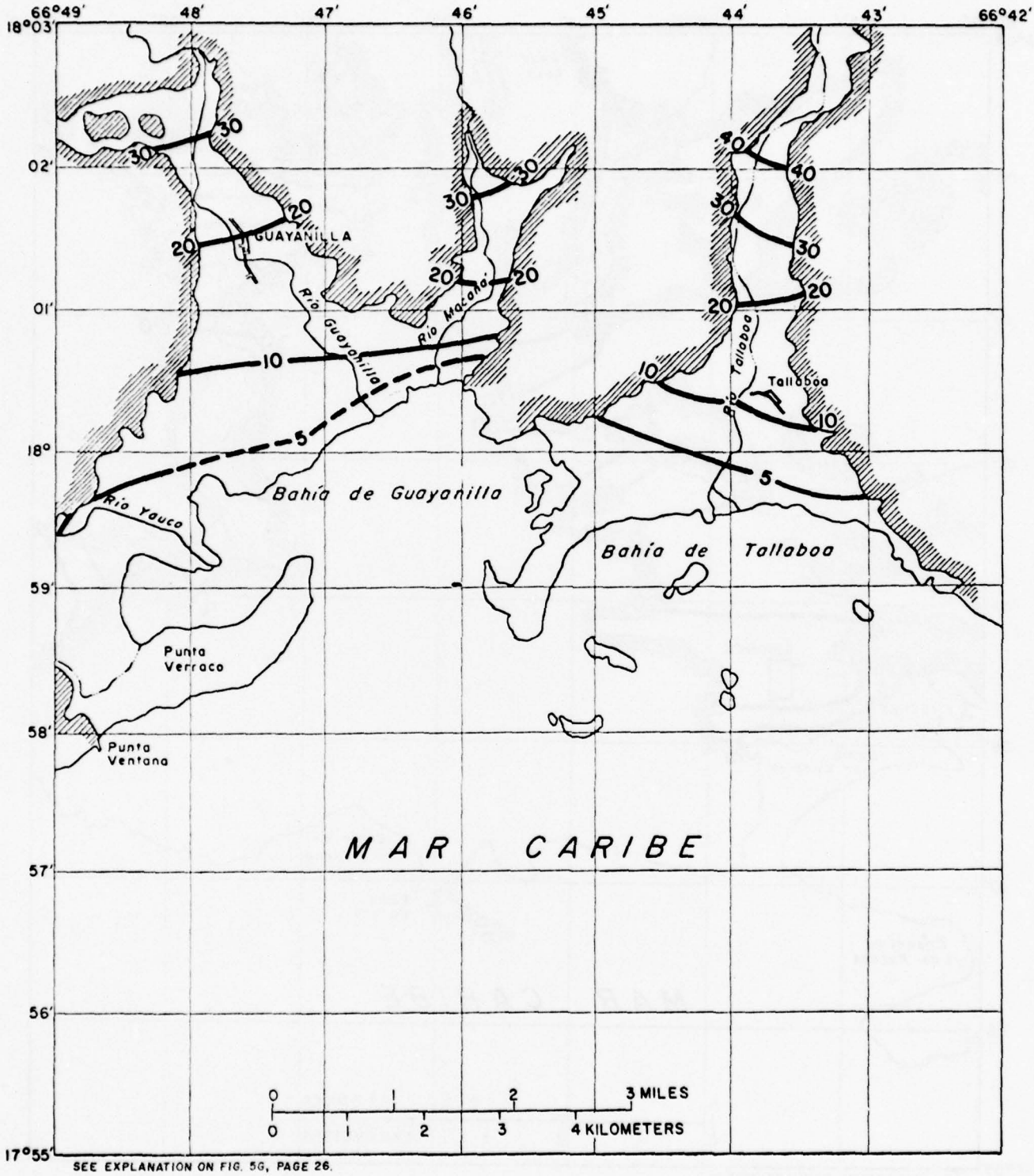


Figure 5b.--Simulated water levels resulting from average boundary condtions in the Guayanilla-Tallaboa area.

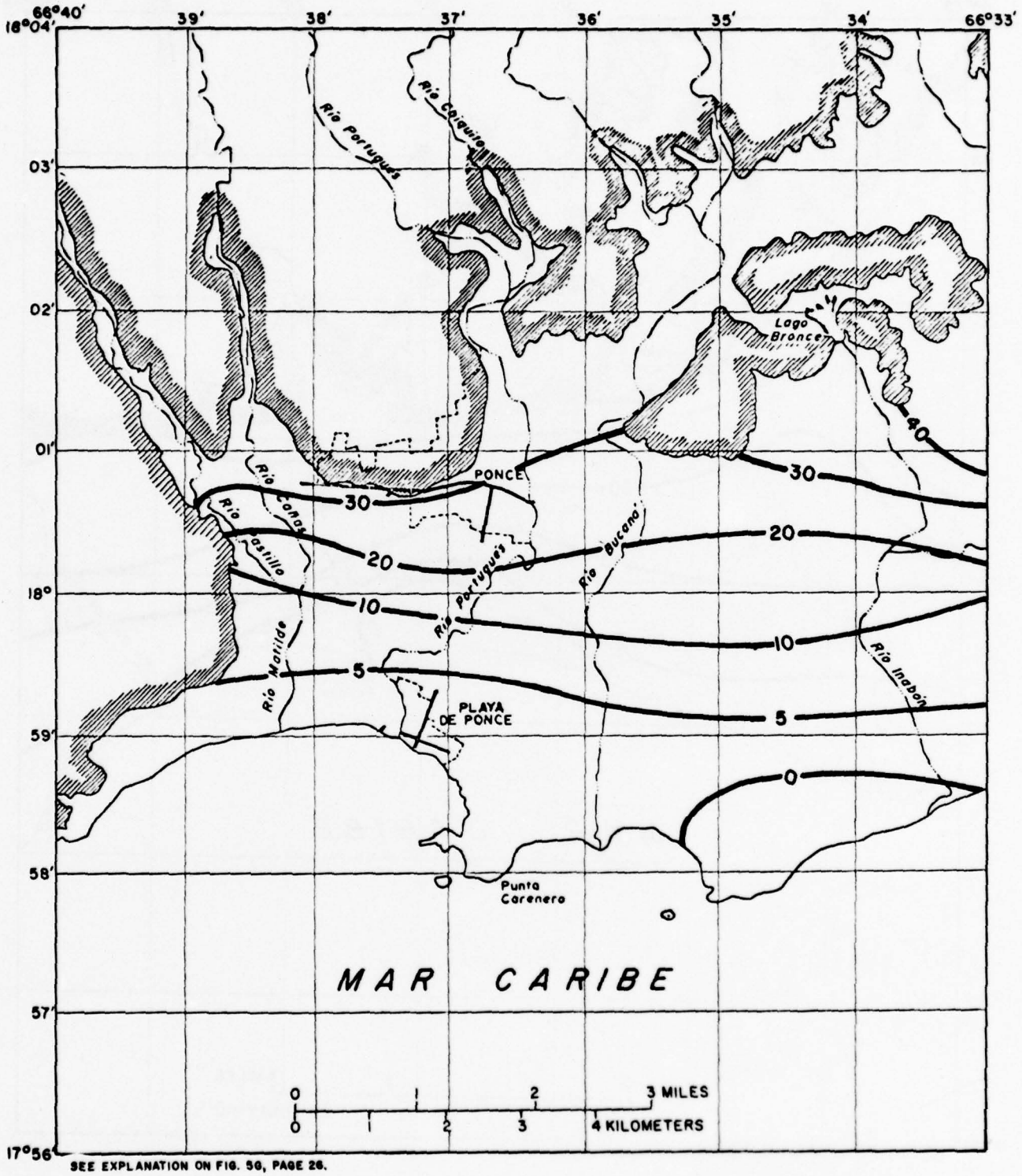


Figure 5c.--Simulated water levels resulting from average boundary conditions in the Pastillo-Inabón area.

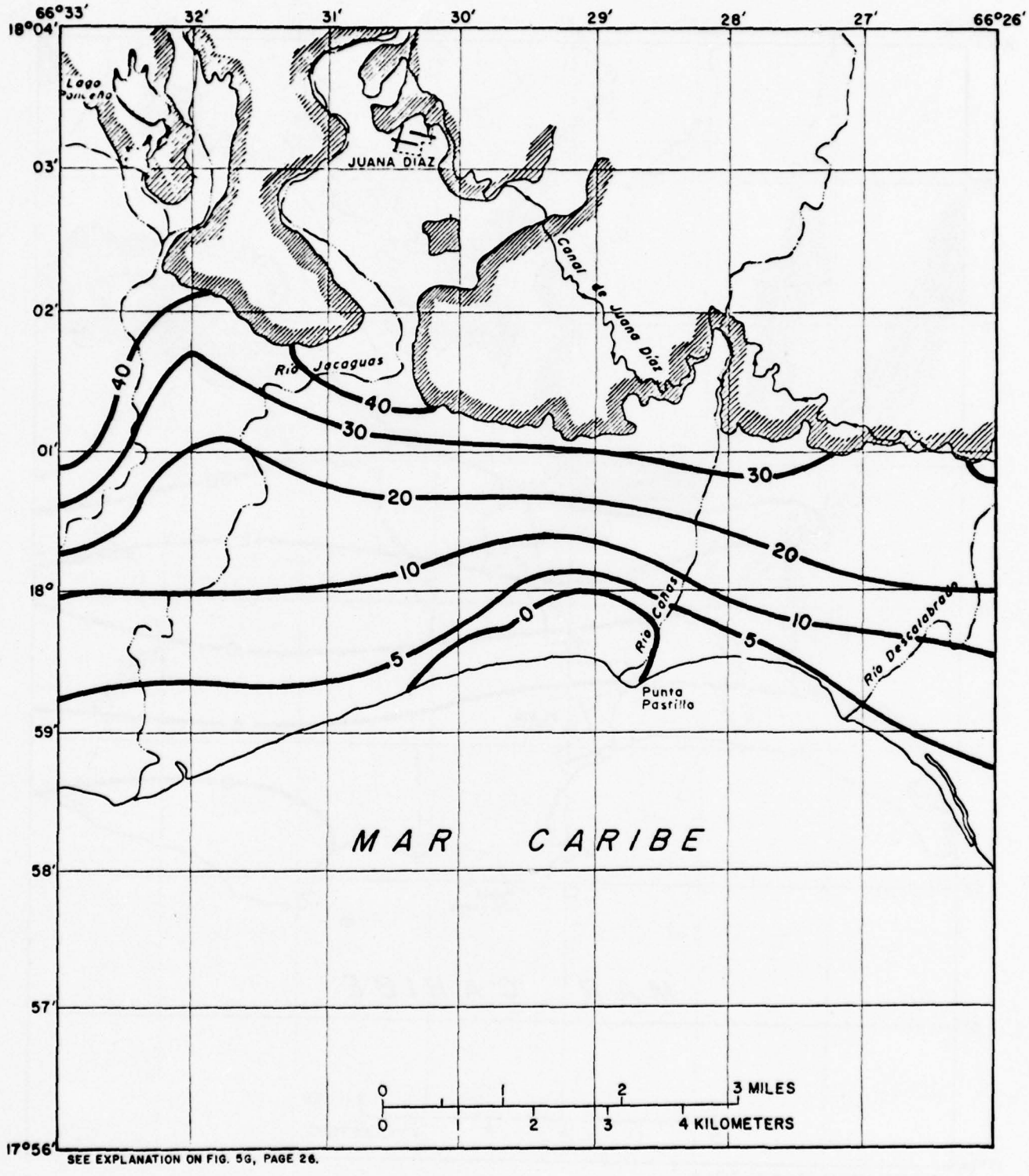


Figure 5d.--Simulated water levels resulting from average boundary conditions in the Juana Díaz area.

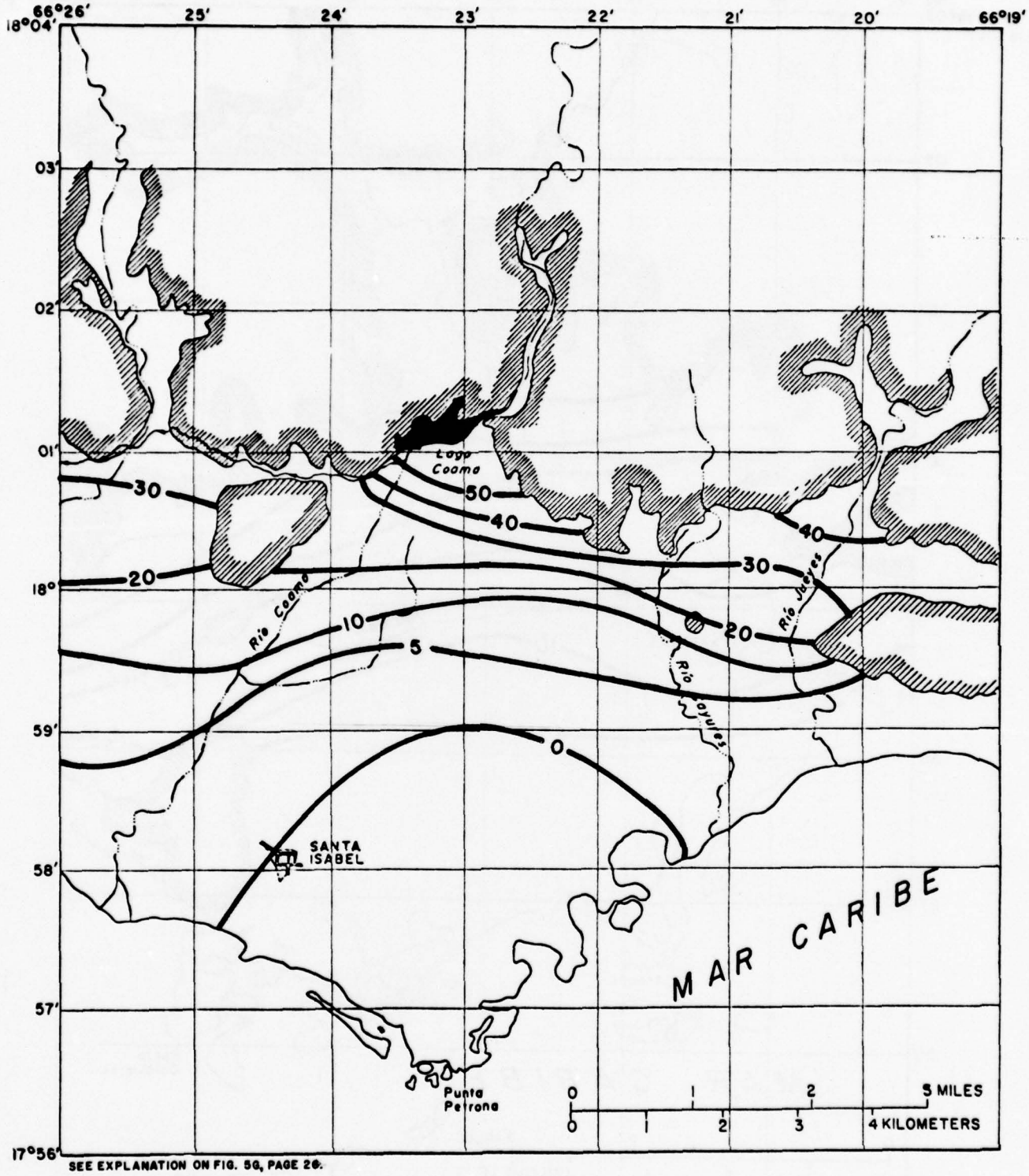


Figure 5e.--Simulated water levels resulting from average boundary conditions in the Coamo area.

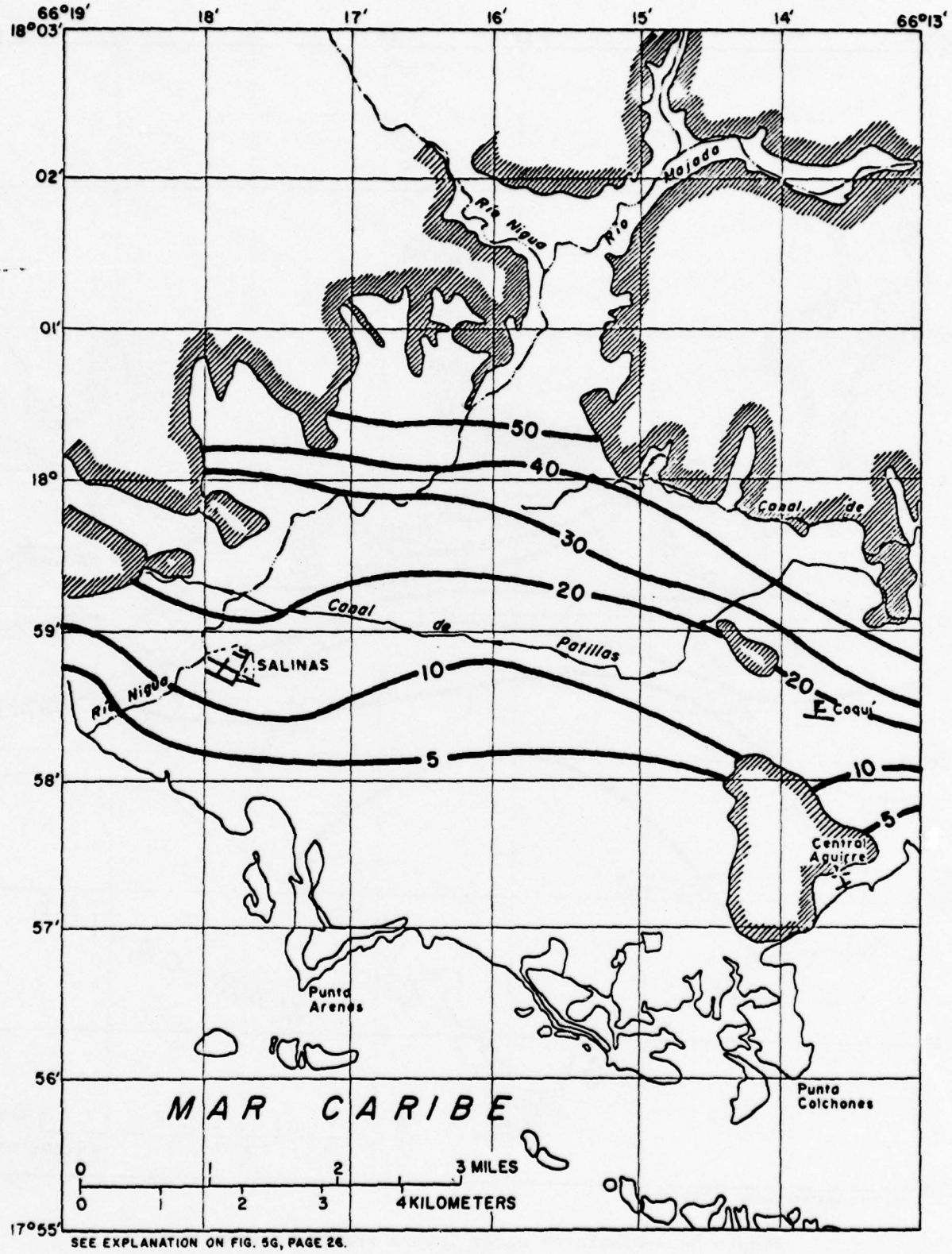


Figure 5f.--Simulated water levels resulting from average boundary conditions in the Salinas area.

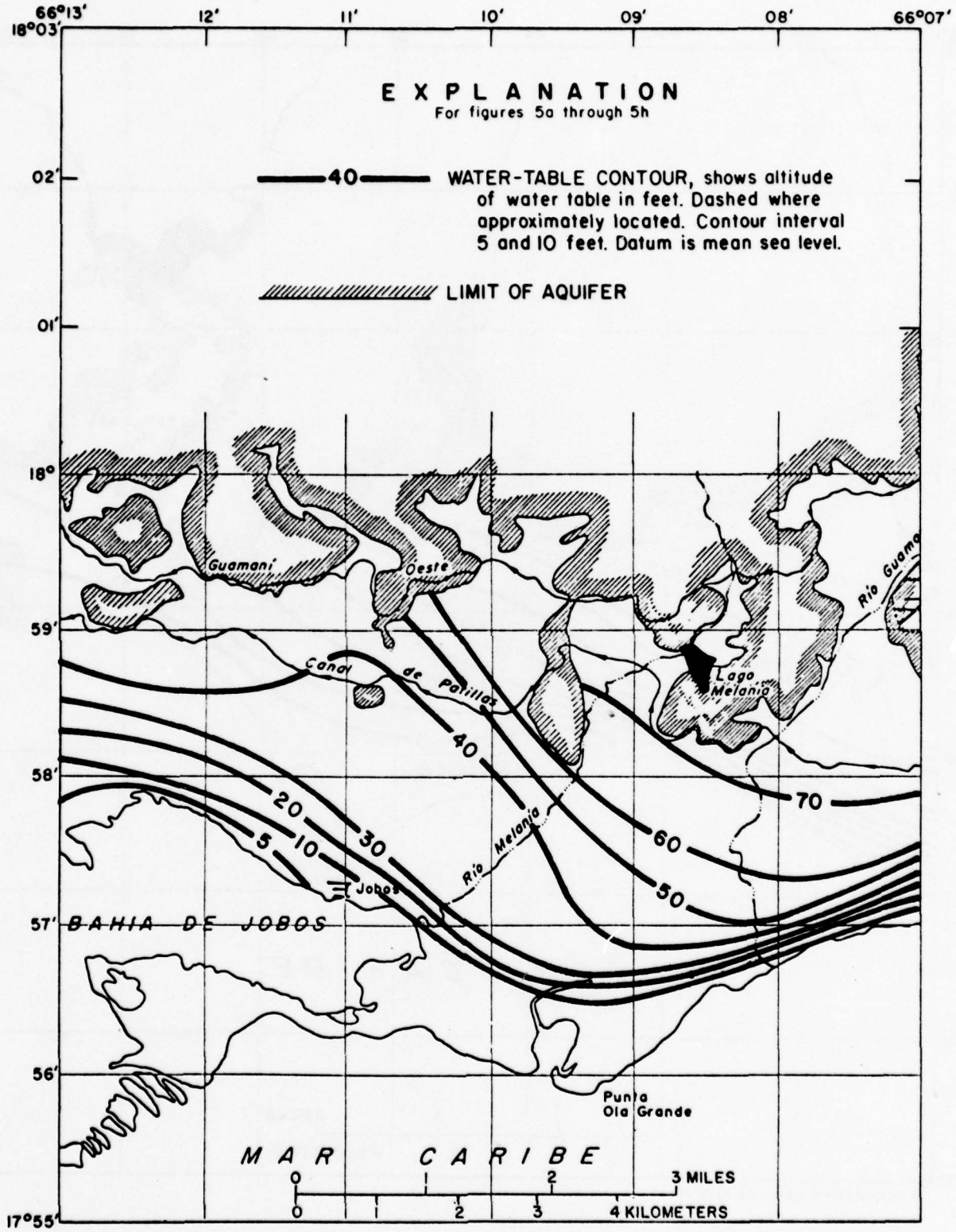


Figure 5g.--Simulated water levels resulting from average boundary conditions in the Jobos area.

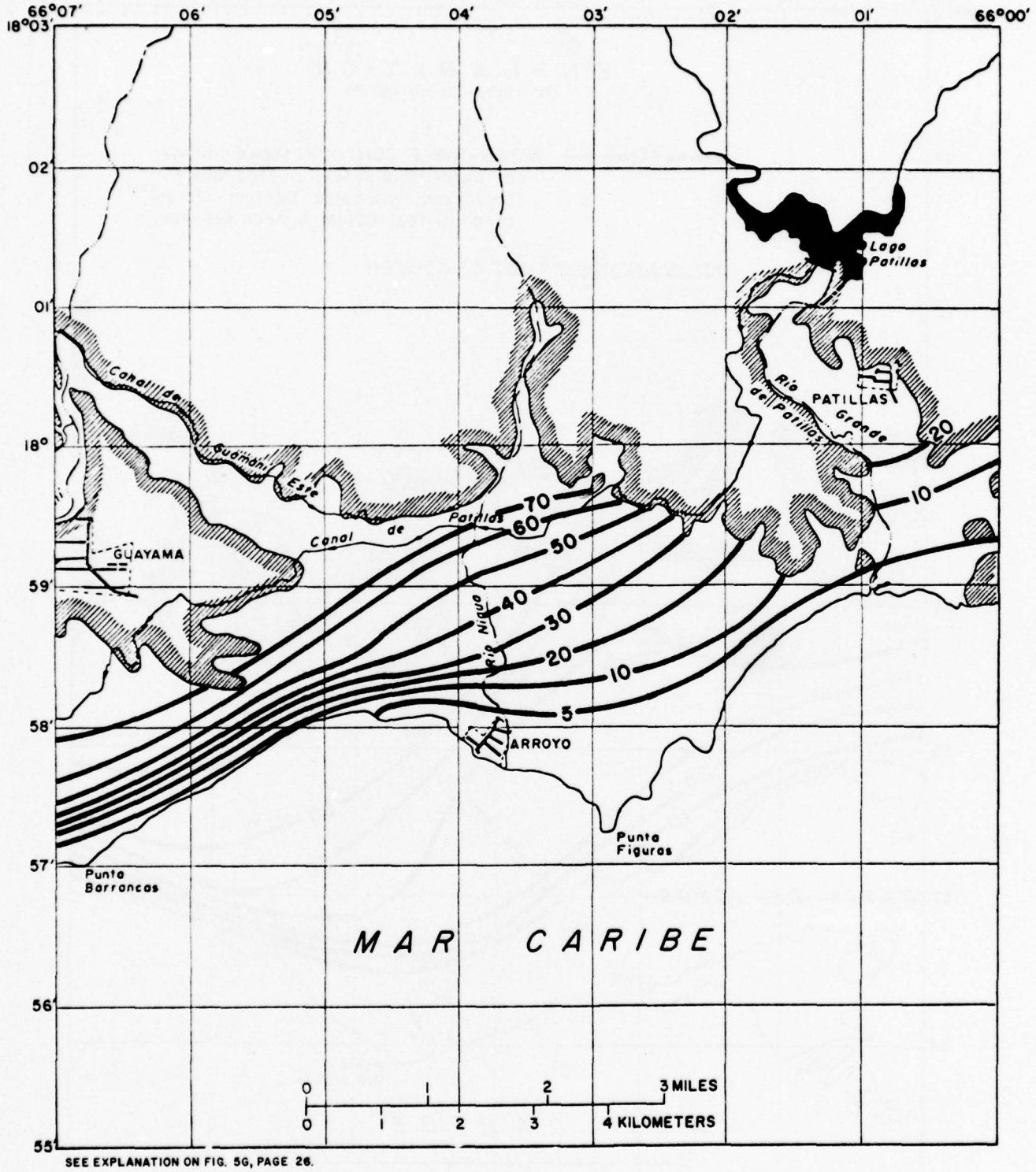


Figure 5h.--Simulated water levels resulting from average boundary conditions in the Guayama-Patillas area.

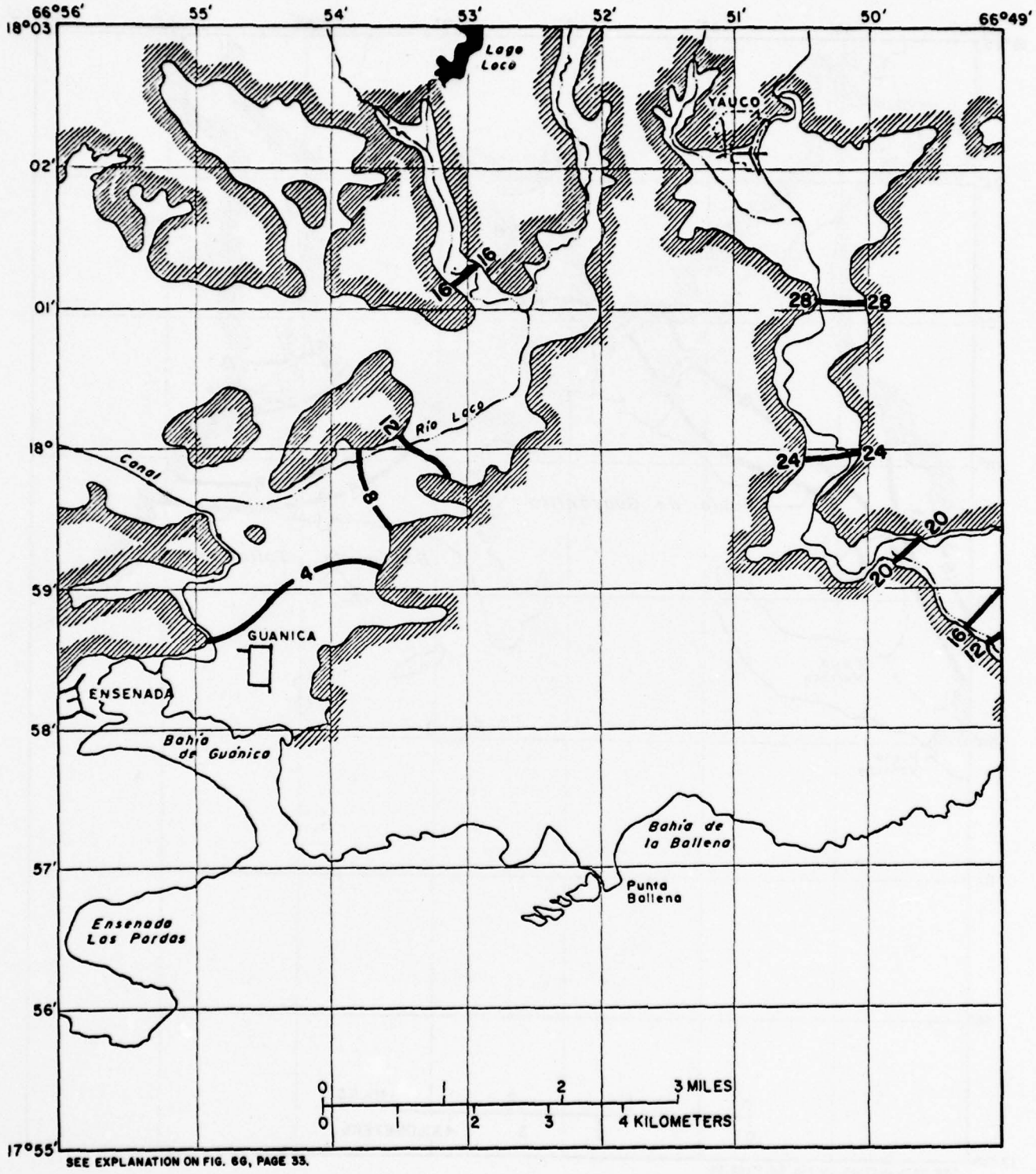


Figure 6a.--Simulated water-level changes for a drought period in the Guánica-Yauco area.

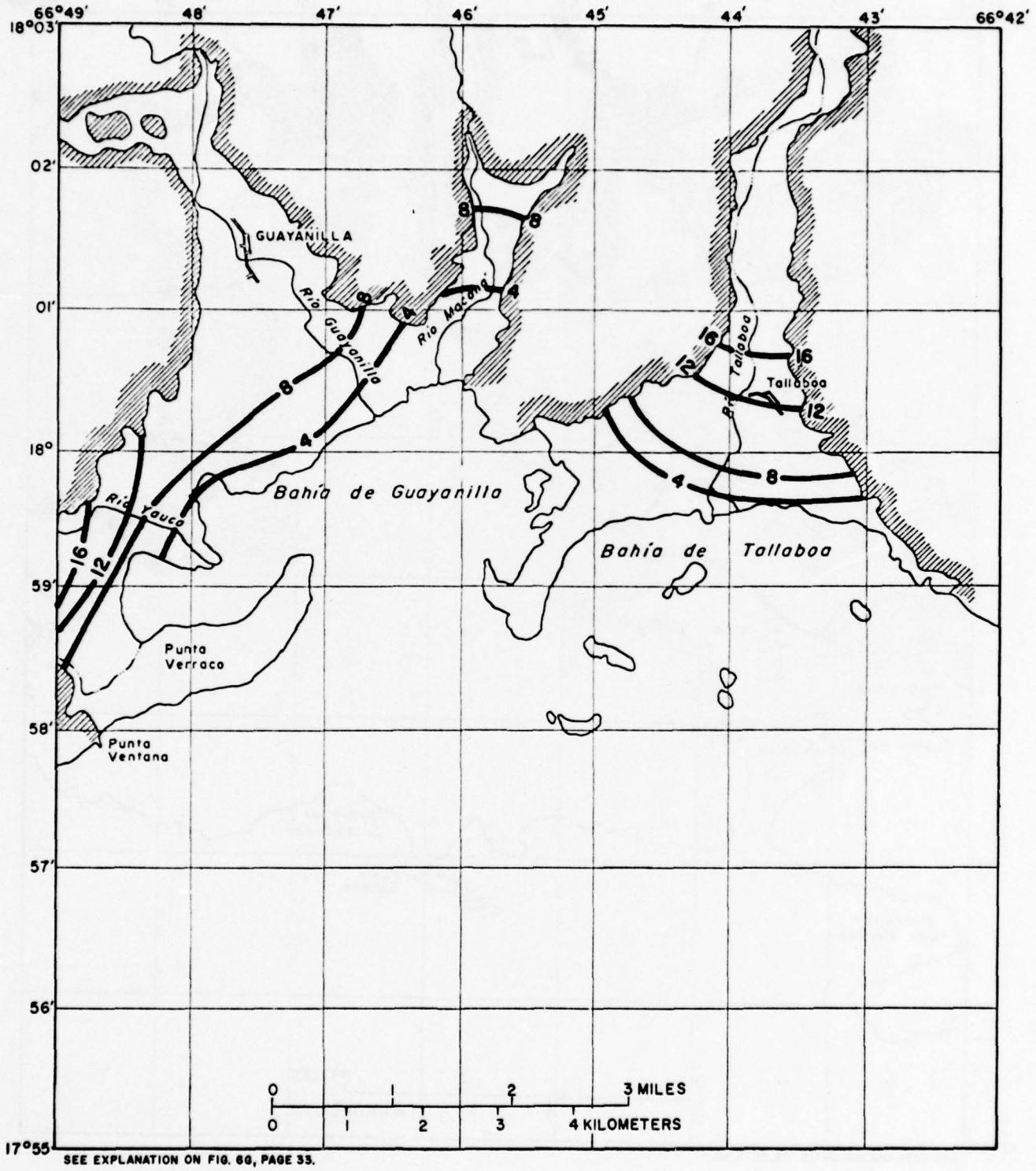


Figure 6b.--Simulated water-level changes for a drought period in the Guayanilla-Tallaboa area.

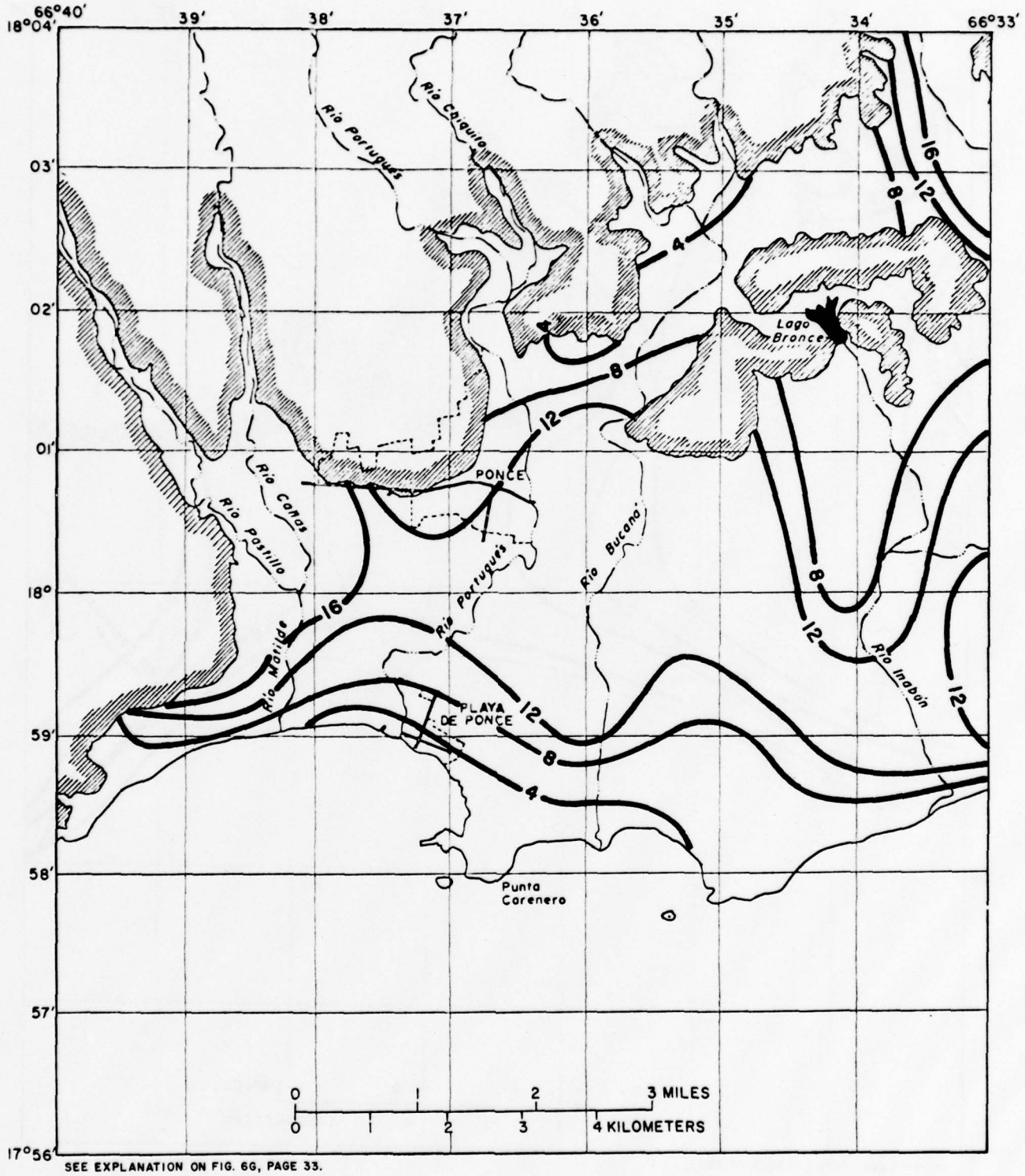


Figure 6c.--Simulated water-level changes for a drought period in the Pastillo-Inabón area.

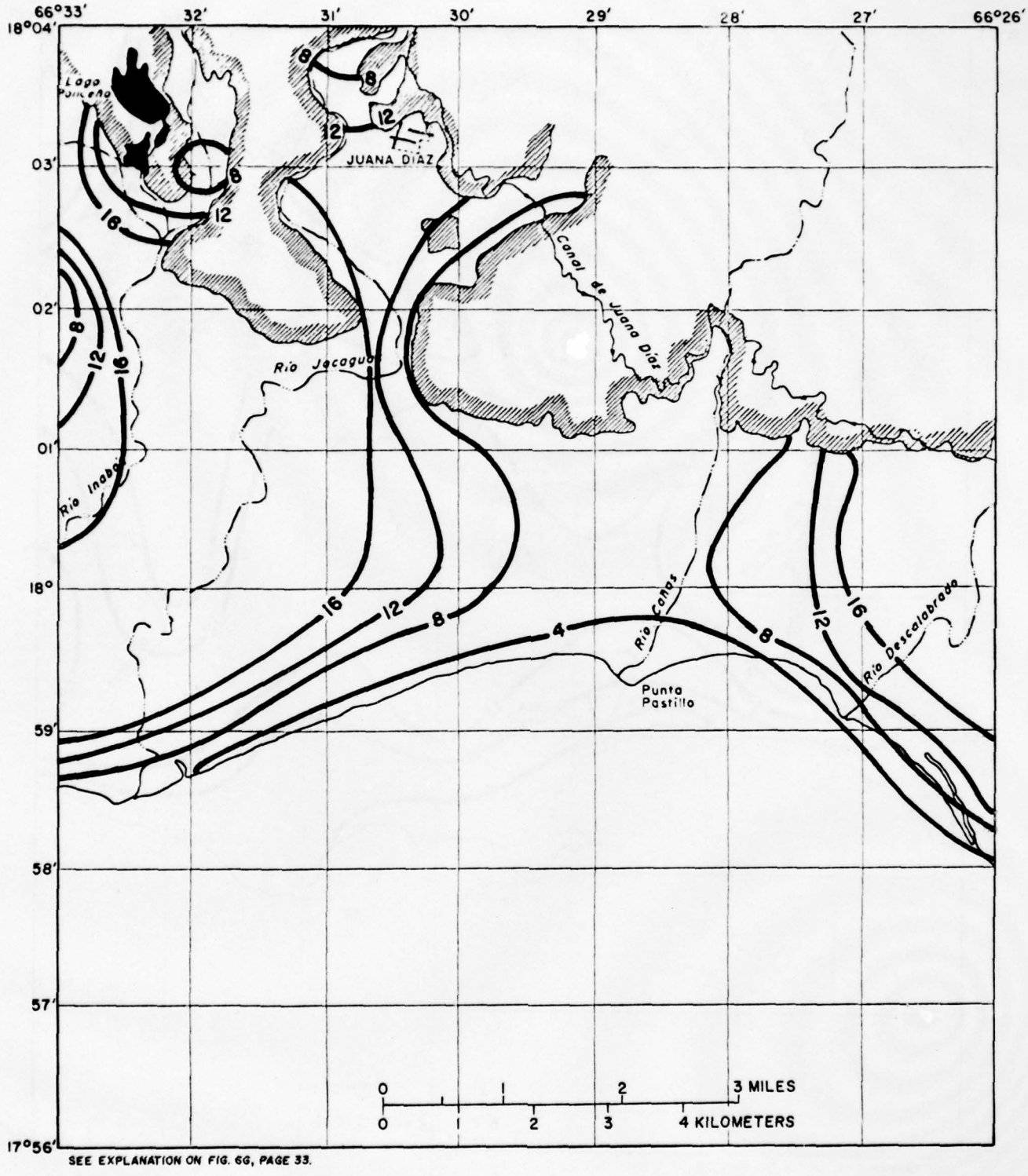


Figure 6d.--Simulated water-level changes for a drought period in the Juan Díaz area.

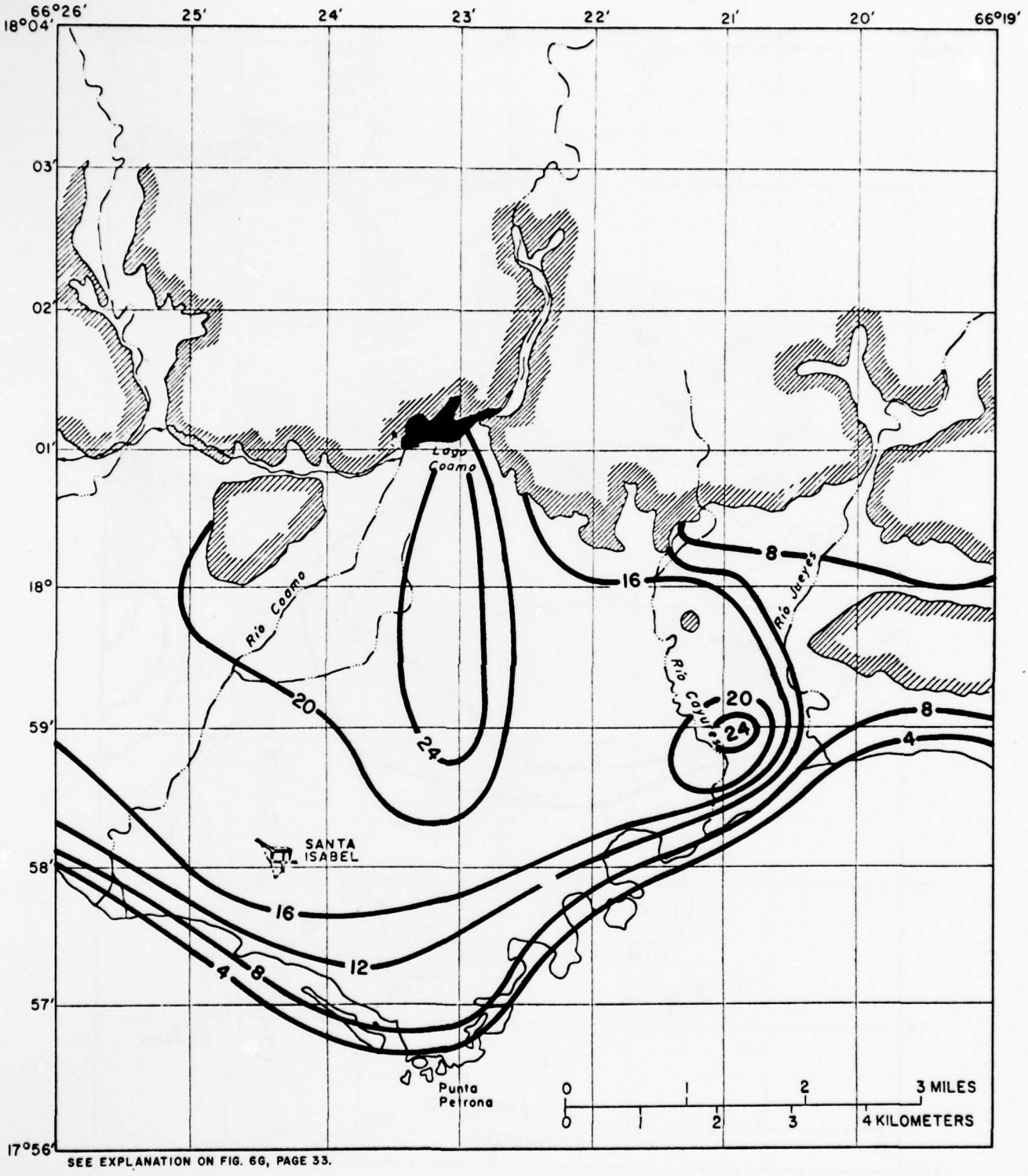


Figure 6e.--Simulated water-level changes for a drought period in the Coamo area.

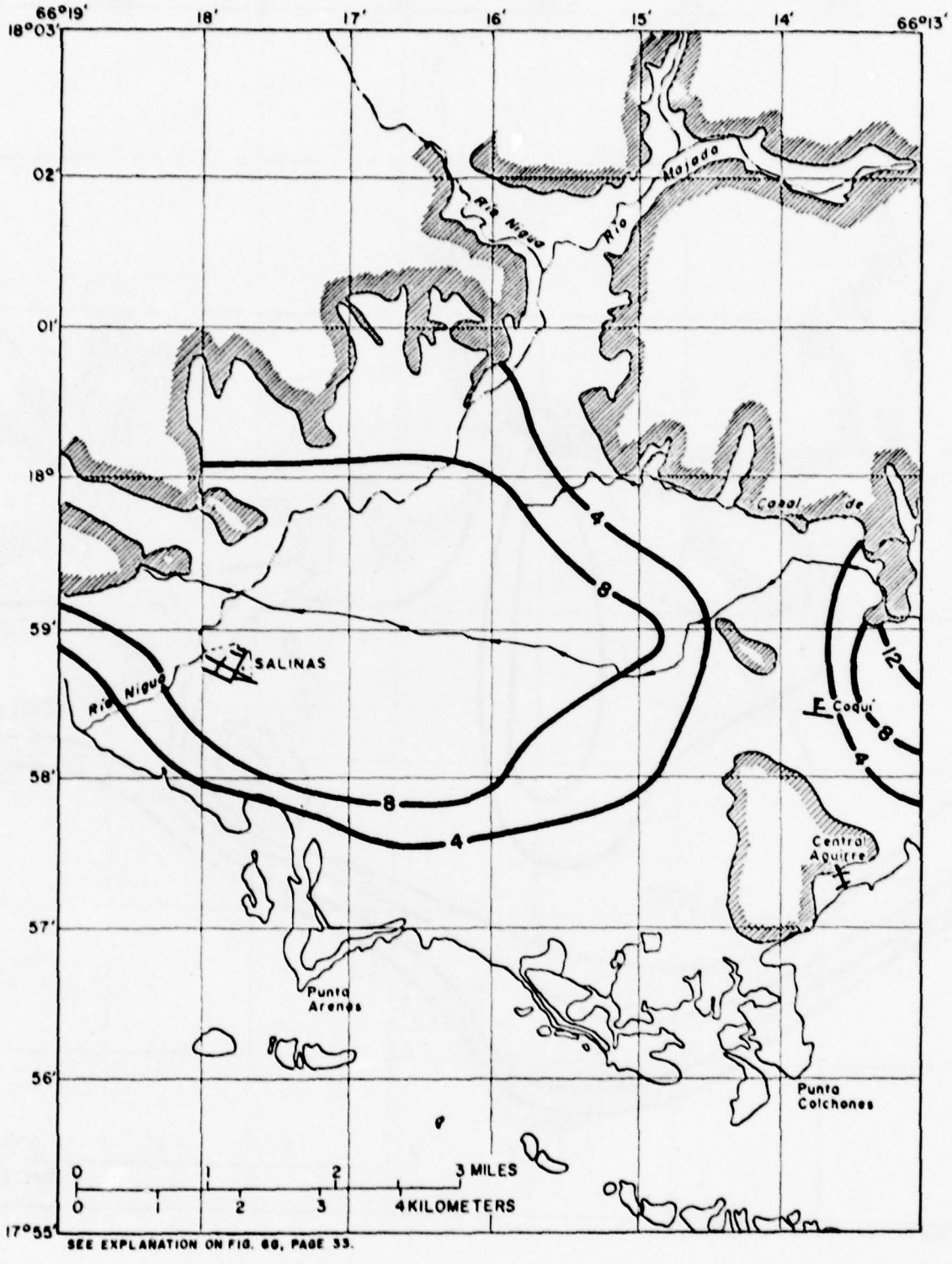


Figure 6f.--Simulated water-level changes for a drought period in the Salinas area.

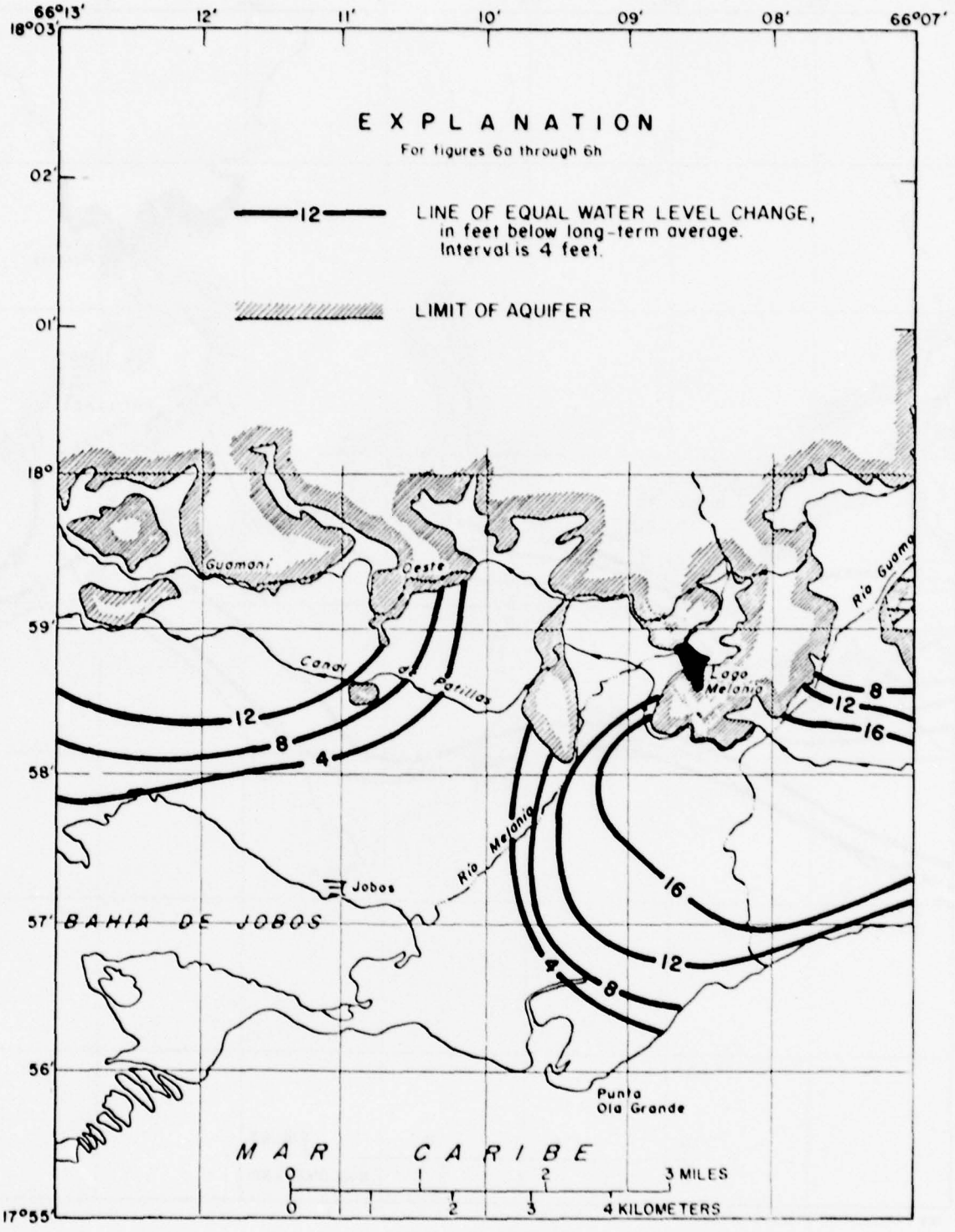


Figure 6g.--Simulated water-level changes for a drought period in the Jobos area.

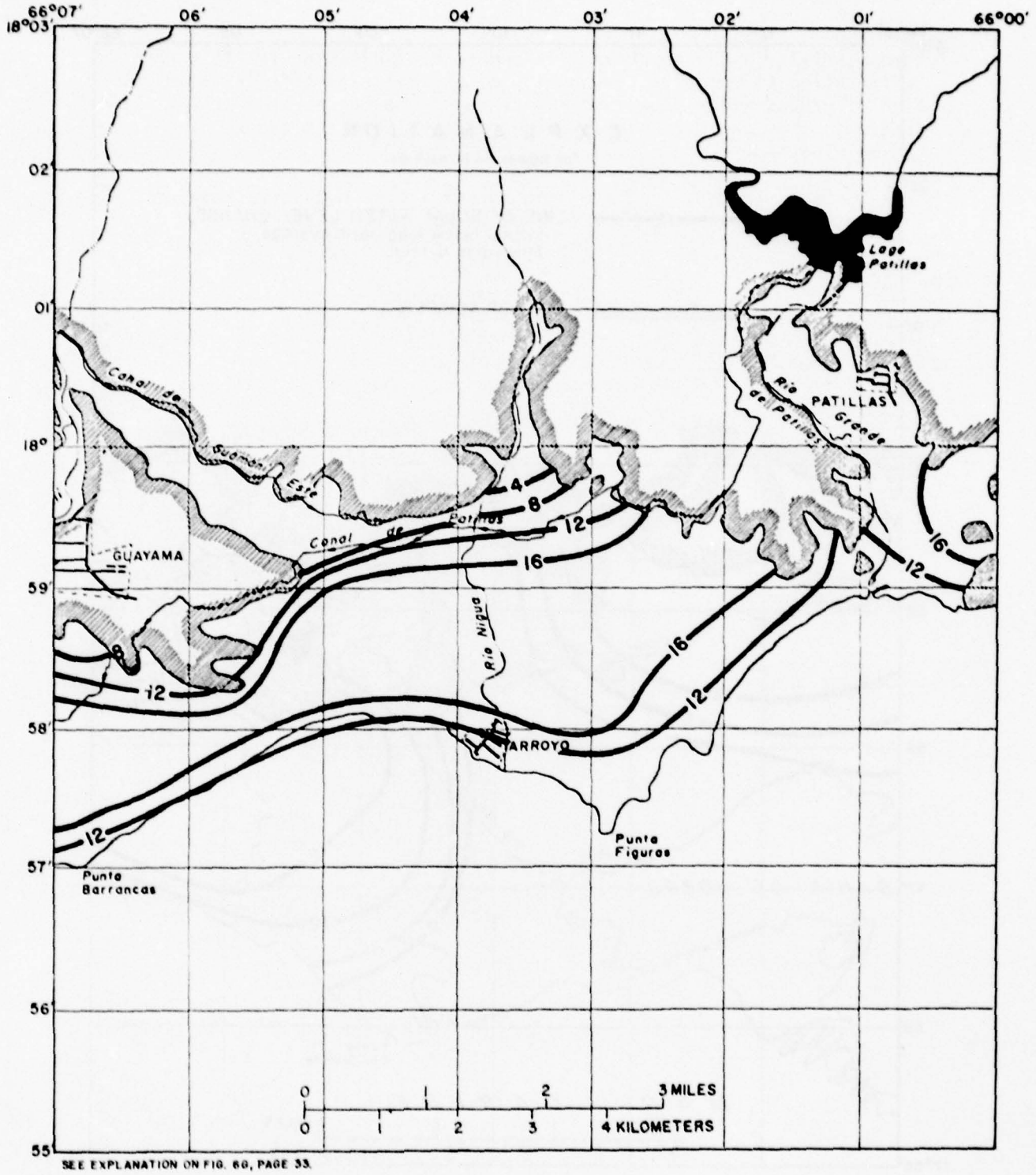


Figure 6h.--Simulated water-level changes for a drought period in the Guayama-Patillas area.

transmissivity. The topography is a determining factor in ratio of infiltration to runoff. Homogeneity of the material affects the direction of ground-water flow, and the depth of the unsaturated zone limits the gradients that can be built up which, in turn limit the amount of water that can be distributed.

Probably the greatest limiting factor is the hydraulic conductivity. The range of hydraulic conductivities found on the south coast is great--from less than 25 ft/d (feet per day) to greater than 350 ft/d (Bennett, 1976, fig. 3).

Considering equal sections of aquifer and equal gradients, 14 times more water will move through an area with 350 ft/d hydraulic conductivity than through an area with a hydraulic conductivity of 25 ft/d. Studying the map of hydraulic conductivity as presented by Bennett (1976, in fig. 3) will aid in locating favorable areas for moving water through the aquifer. The hydraulic conductivity in the areas where recharge experiments were performed ranged from less than 25 to over 200 ft/d, with only a limited area greater than 200 ft/d and most areas less than 50 ft/d.

Transmissivity is defined as the depth of the saturated zone times its hydraulic conductivity. Larger transmissivity values are more desirable for moving water than smaller values. On the south coast the most favorable hydraulic conductivities occur in areas that are relatively shallow (less than 100 ft) so hydraulic conductivity alone does not qualify for a selection criterion.

Differences in specific yield theoretically have no influence on an equilibrium operation. In practice, however, recharge is normally managed on a rotating-area or intermittent-application plan, and in such an operation, areas of larger specific yield would tend to be more desirable because they could accept greater volumes of water during each period of application. Differences in specific yield have not been identified in the alluvial aquifers on the south coast.

Topographic considerations are two: slope and relief. A low slope is desirable in that this condition favors infiltration rather than runoff. On the other hand, if maintenance of stream base flow is an objective, it may be desirable to utilize an area with some relief in order to favor recirculation of the recharged water to the streams.

The aquifer material on the south coast varies considerably from place to place, and direction of ground-water flow is in part controlled by these variations. The model incorporates these changes in a horizontal direction and to a limited degree in the vertical direction. The model is not designed to simulate soil zone materials, or conditions in the unsaturated zone in general. Thus there is an assumption, throughout this analysis, that the hydraulic conductivity of the soil to unsaturated flow will not be a limiting factor, but rather will be sufficient to transmit whatever recharge the aquifer can accept. This is, of course, a limitation of the analysis.

Water can be induced to flow in an aquifer by creating a head difference or gradient--the larger the gradient, the greater the flow for any given place. The largest gradient that can be established in a water-table aquifer occurs when the water table is raised to the land surface in the area of application. Thus a limit to the gradient, and also to the amount of water that can be applied is established by the depth to water table below land surface. For an effective recharge operation, this depth should be relatively great; areas along the shore must therefore be eliminated from consideration, because the water table is very close to ground surface in these areas. Unfortunately, the deepest parts of the aquifers are along the coast. The most favorable areas for recharge thus appear to be those midway between the coast and the foothills where the aquifers exhibit some thickness and transmissivity, but water levels are at a reasonable depth below ground surface.

When water is added to the aquifer either by infiltration basin techniques or by irrigation, an increase in water level will occur. This increases the saturated thickness and therefore the transmissivity of the aquifer. The model does not compensate for this increase in transmissivity; however, for the most part this increase is small compared to the thickness of the aquifer and the additional saturated thickness will not carry enough water to affect the estimates significantly. Because of the way the alluvium was deposited, finer-grained material is normally at the top of the formation and the upper zone, when saturated, will not contribute as much to the transmissivity as the lower, main part of the aquifer.

In all simulations it was assumed that present recharge was sufficient to maintain water levels as they are and additional recharge would be responsible for water-level changes. It is understood that under actual conditions at times there will be large natural recharge events, as well as times when natural recharge is insufficient to maintain water levels.

Because all the irrigation problems were formulated assuming that 70 percent of the water will be lost through the process of evapotranspiration, it is necessary to consider that the amount of recharge may be limited by the ET (evapotranspiration). For the ET function shown in figure 2, when the ground is saturated to the surface, a maximum of 0.014 ft/d will be required for ET. This amounts to 4,600 (gal/d)/acre (gallons per day per acre), which is 70 percent of 6,600 (gal/d)/acre. Theoretically, 6,600 (gal/d)/acre is the maximum that can be applied. It would take more than 150 acres to apply 1 Mgal/d under saturated conditions when 70 percent of the water loss would be through ET.

There are two variables affecting this consideration: (1) the ET rate, and (2) the ratio of infiltration to application. These are assumed quantities and if either of these is different, different amounts of water could be applied. Estimates of the ratio of infiltration to application have been made for many areas on the south coast and were listed earlier under recharge sources (p. 5).

Artificial Recharge Possibilities

When a supplemental recharge is applied to an aquifer, the water may be applied as irrigation; it may be spread on the ground as in an infiltration gallery or basin; or it may be forced into the ground as in deep-well injection. All these possibilities were investigated with certain assumptions made for the different methods.

Irrigation

An extensive surface-water irrigation system that covers most of the south coast is operated by the WRA (Water Resources Authority) of the Puerto Rico government. The WRA is not always able to supply all the water required by the crops and attempts have been made to find a more effective way of irrigating so that water could be conserved. Waste water could be used to supplement irrigation supplies on the south coast. Assuming quality, health, and aesthetic standards could be met, potential advantages are:

1. Land need not be taken out of production.
2. More water would be available for irrigation.
3. The problem of disposing of the waste water would be solved.
4. Excess water would infiltrate to the aquifer and provide needed recharge.

A disadvantage of using waste water for irrigation is that only part of the water would recharge the aquifer. However, other water supplies would be relieved partially of the irrigation burden and those supplies could provide water to other areas or for other needs.

In the operation of the model, irrigation is simulated by spreading the input over an area that is indicated for each location. It is assumed that 70 percent of the water applied was either used by the crops or lost to evaporation. The remaining 30 percent is available for ground-water recharge. The value reported is the total water applied and not the 30 percent that reaches the water table. In the actual simulation the 30 percent was applied to the model.

Infiltration-Percolation

The model also was used to simulate the response of the aquifer to a hypothetical IP (infiltration-percolation) problem. Various amounts of current were injected in selected groups of nodes in the uppermost layer of the model to simulate different loading rates. The water was assumed to be "ponded" over the aquifer and by infiltration-percolation to recharge the

ground water. Each node in the immediate area was monitored to record the simulated change in water level. The computed ground-water-level-rise values for each nodal point suggest to what degree the modeled aquifer systems can be recharged.

The amount of water simulated in the model for the IP problem was 90 percent of the value stated in the problems. The remaining 10 percent was assumed to be lost to evapotranspiration.

No attempt was made to simulate the vertical movement of water from land surface to the aquifer. The gradients established are those necessary to move the water horizontally in the aquifer. Similarly, no attempt was made to simulate unsaturated vertical flow which would occur at the beginning of a field trial.

The aquifer is kept saturated to the surface for IP applications. The water-level gradient established in the direction away from the perimeter of the plot is the determining factor as far as how much water can be applied. Water-level changes within the plot area have no meaning because they are no longer governed by the aquifer parameters.

Deep-Well Injection

In the Ponce area, a series of three tests were simulated to determine the feasibility of deep-well injection. In this operation water is injected directly into the active part of the aquifer with no evapotranspiration loss. In actual practice it would be necessary to provide a high degree of purification for the waste water to minimize operating problems with the injection well. The current in the injection experiments was fed into the second layer of the model.

Test Areas

The test areas included the alluvial aquifers of the Río Yauco Valley, Guayanilla Valley, Tallaboa Valley, Mercedita area, Pastillo-Cañas Valley northwest of Ponce, and the Jobos and Guayama areas. These areas were selected because they are relatively close to the regional treatment plants proposed by the Aqueduct and Sewer Authority. The areas of Guayanilla and Yauco could receive water from the Guayanilla regional waste treatment plant. The areas of Tallaboa Valley, Mercedita and Pastillo-Cañas Valley could be supplied by the Ponce regional waste treatment plant. The Jobos and Guayama areas could be supplied by the Guayama regional waste treatment plant.

In all test areas the inland limit of the alluvial aquifer was taken as the bedrock alluvium contact which is approximately the 160-ft altitude contour.

There were many tests run in the different areas. Table 1 is a summary of all the tests performed. Many of those listed are not described in this report because so much of the information would be repetitive and would transfer little knowledge. The tests that are described form a framework into which other possible application values can be placed.

Río Yauco Valley

The alluvium in the Yauco Valley occupies a narrow trough that ranges from less than 1/2 to about 1 mi in width. The alluvium of the upper third of the valley is seldom more than 40 ft thick and is composed of cobbles and boulders interbedded with thin clayey sand and gravel. Relatively impermeable volcanic and sedimentary rocks underlie the alluvium and form the valley walls.

The alluvium of the central third of the valley exceeds 100 ft in thickness and is composed of sand and gravel interbedded and intermixed with clay and silt. In general the greatest thickness and more permeable alluvium lies in the center of the valley and becomes thinner and more clayey toward the valley walls. A chalky limestone underlies the alluvium and forms the valley walls. The limestone of the immediate valley wall generally is of greater permeability than that beneath the adjacent hills and that which underlies the alluvium in the valley floor.

Irrigation simulations.--Irrigation simulations were made using two areas of about equal size--both in the middle reach of the valley. Together the two areas cover about 590 acres. The simulations represent conditions which would occur if irrigation water were applied at rates ranging from 1 to 80 Mgal/d for 35 days and 1-year periods over the entire 590 acres.

Figure 7 is a map of the Yauco Valley showing the depth to water in wells in February 1975; lines of equal depth to water; and the location of areas used for the irrigation simulation. Static water levels were used to determine the lines of equal depth to water. There is approximately 20 ft of unsaturated material in the central third of the Yauco Valley, and it was assumed that recharge could be applied until the water levels rose 16 to 18 ft in this area.

Figure 8 is a graph showing the relationships between water applied and water-level rise for both the 35-day period and the 1-year period.

Changes in water levels in the aquifer resulting from simulated irrigation water appled at varying rates to the 590 acres for periods of 35 days and 1 year are given in table 2. Figure 7 shows that about 20 feet of unsaturated aquifer underlies about half the irrigated area and an average of about 10 feet of unsaturated aquifer underlies the remainder of the irrigated area. If water levels were raised to within 5 ft of land surface, water

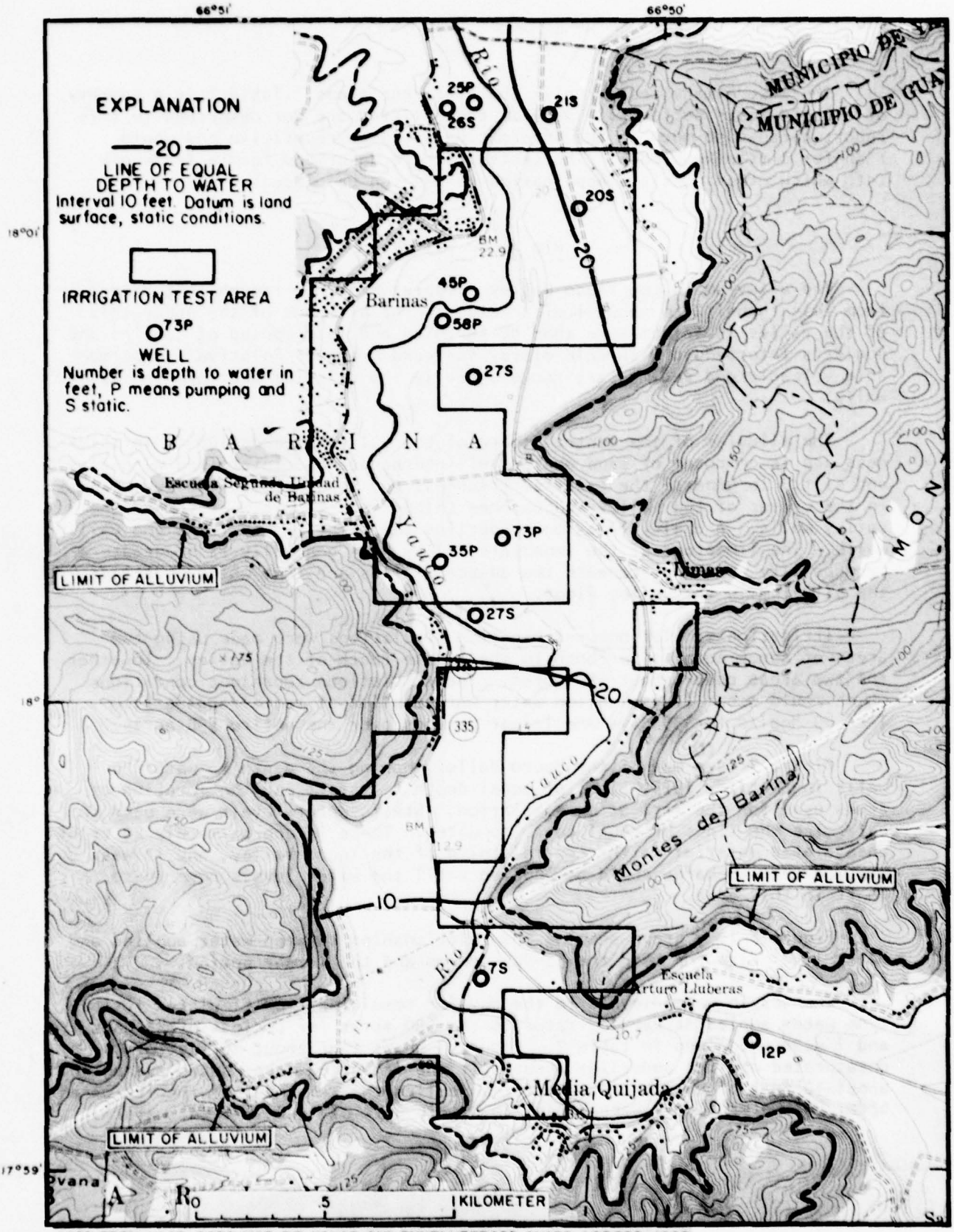


Figure 7.--Depth to water in February 1975, and locations of irrigation simulations in the Yauco area.

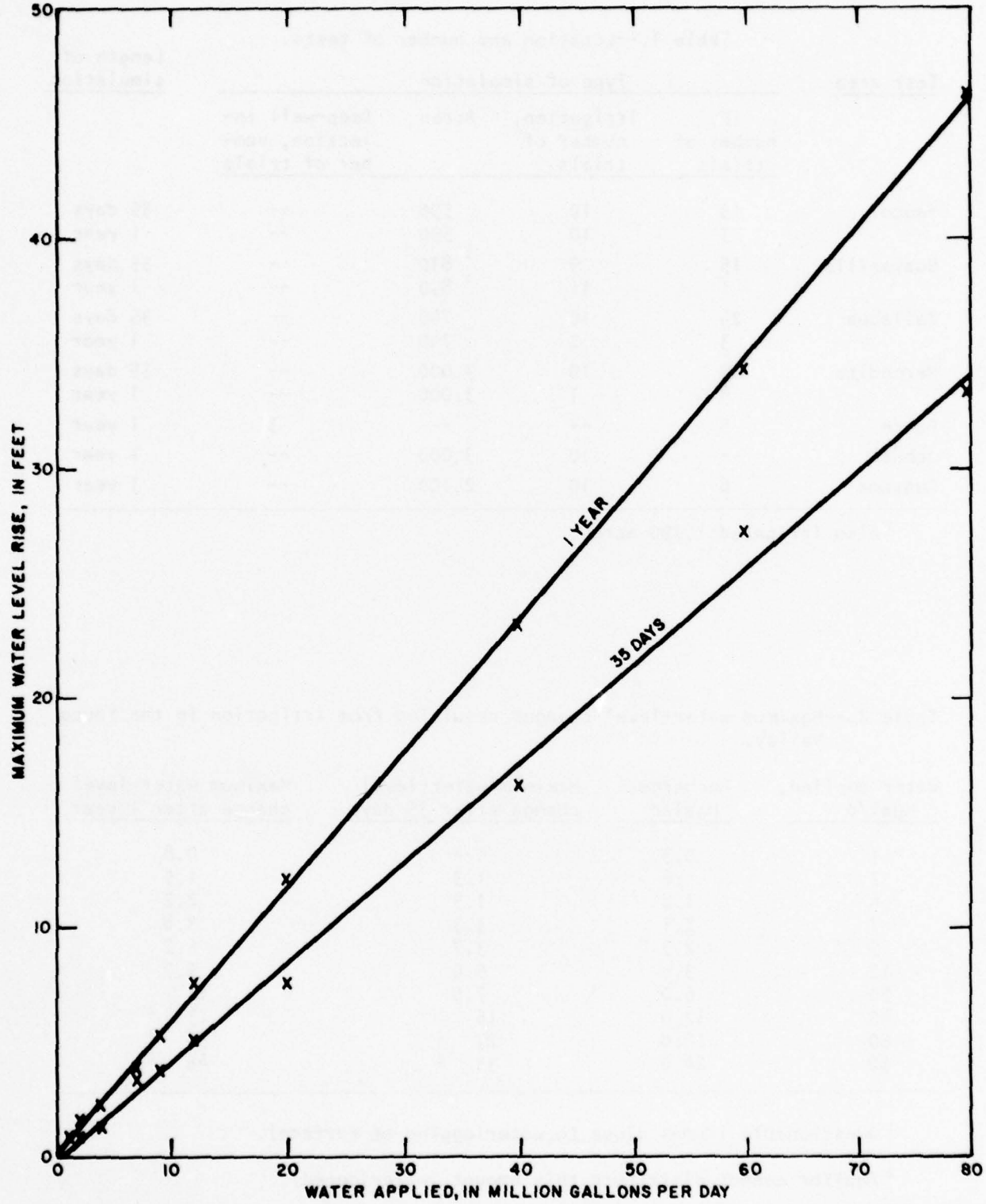


Figure 8.--Relationship between maximum water-level rise and amount of water applied for simulated irrigation in the Yauco Valley.

Table 1.--Location and number of tests.

Test area	Type of simulation				Length of simulation
	IP, number of trials	Irrigation, number of trials	Acres	Deep-well injection, number of trials	
Yauco	13	10	590	--	35 days
	3	10	590	--	1 year
Guayanilla	15	9	[1] 830	--	35 days
	1	11	[1] 830	--	1 year
Tallaboa	24	10	740	--	35 days
	3	2	740	--	1 year
Mercedita	19	10	3,000	--	35 days
	4	1	3,000	--	1 year
Ponce	5	--	--	3	1 year
Jobos	--	10	3,000	--	1 year
Guayama	6	10	2,100	--	1 year

[1] Also irrigated 1,790 acres.

Table 2.--Maximum water-level changes resulting from irrigation in the Yauco Valley.

Water applied, Mgal/d	Recharge, Mgal/d	Maximum water-level change after 35 days	Maximum water-level change after 1 year
1	0.3	--	0.8
2	.6	1.3	1.5
4	1.2	1.3	2.2
7	2.1	3.3	3.8
9	2.7	3.7	5.2
12	3.6	5.0	9.7
20	6.0	7.5	12
40	12.0	16 [1]	23 [2]
60	18.0	27 [2]	34 [2]
80	24.0	33 [2]	46 [2]

[1] Questionable (comes close to waterlogging at surface).

[2] Aquifer cannot distribute this amount (waterlogged).

could be applied at a rate of about 24 Mgal/d for a period of 35 days and at a rate of about 18 Mgal/d for a 1-year period assuming no additional pumping from the aquifer and no additional natural recharge. The area of maximum change is limited.

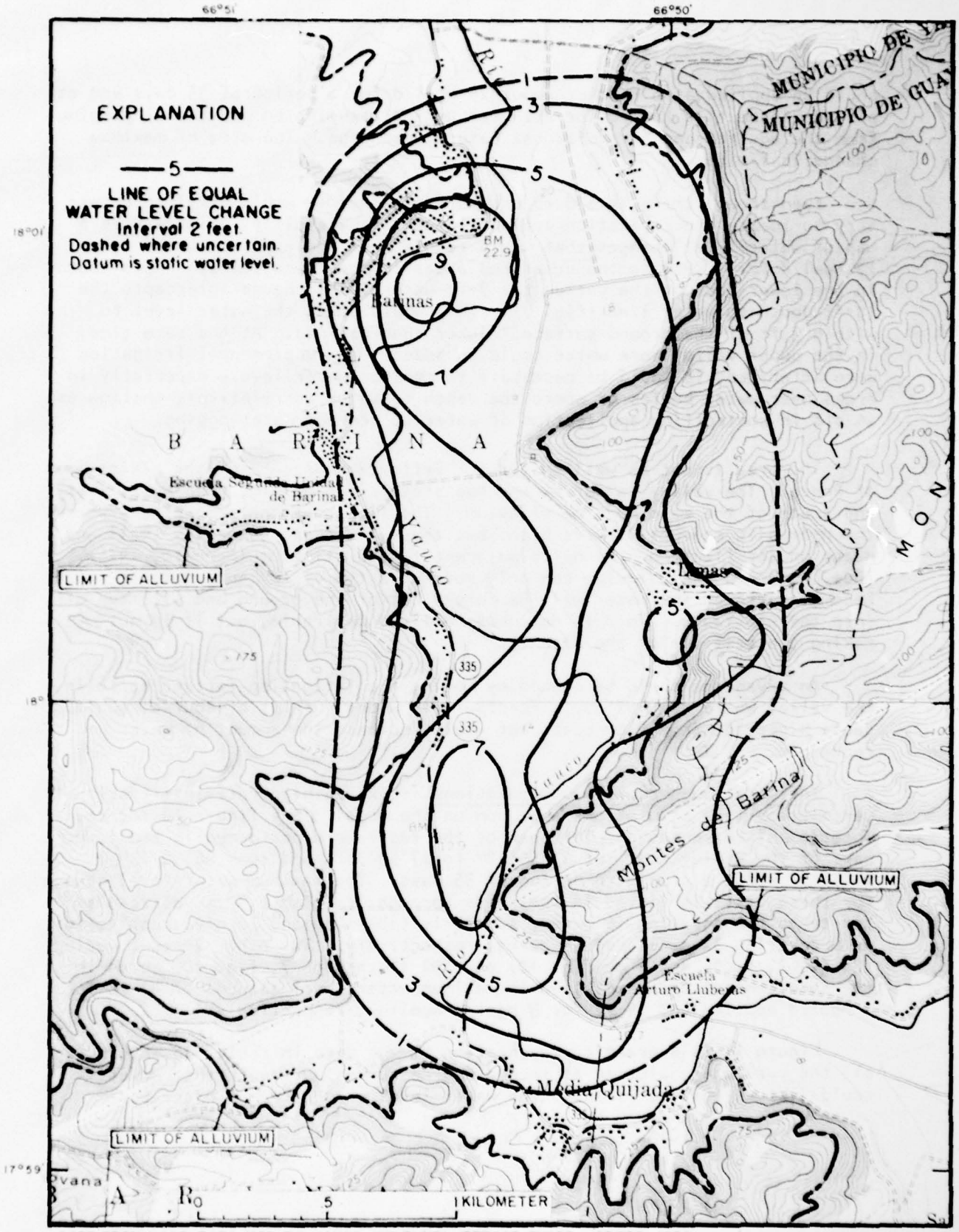
Even though there is a deep unsaturated zone, it would still be necessary to locate the irrigation application areas carefullly. Figure 9 is a map of water-level changes that would result from the application of 12 Mgal/d for 1 year to the described areas in the Yauco Valley. Note that in the lower part of the valley the 7-ft water-level change intercepts the 10-ft depth-to-water line (fig. 7). This would bring the water level to within 3 ft of the ground surface, higher than desired. At the same time, in the upper valley more water could be added. If supplemental irrigation were attempted, it would be necessary to monitor water levels especially in areas near water bodies or where the depth to water is relatively shallow as an aid in controlling application of water to prevent waterlogging.

The area is not as well suited for irrigation as some of the plains east of Ponce. The valley is narrow and has steep sides of limestone east, west, and south of the main body of alluvium. The limestone has some places where the hydraulic conductivity is high, but these areas are generally small and occur on the flanks of the hills adjacent to the alluvium (Bennett, 1976). Thus, water in the alluvium can only move down the valley and where it becomes narrower the water will be forced out of the ground and will run off into the Río Yauco. This is not necessarily undesirable, but it is not making the best use of the water.

An advantage could be gained by moving the irrigation farther north in the valley where the valley is considerably wider. This, of course, would cause higher distribution costs but would increase the amount of water recharged.

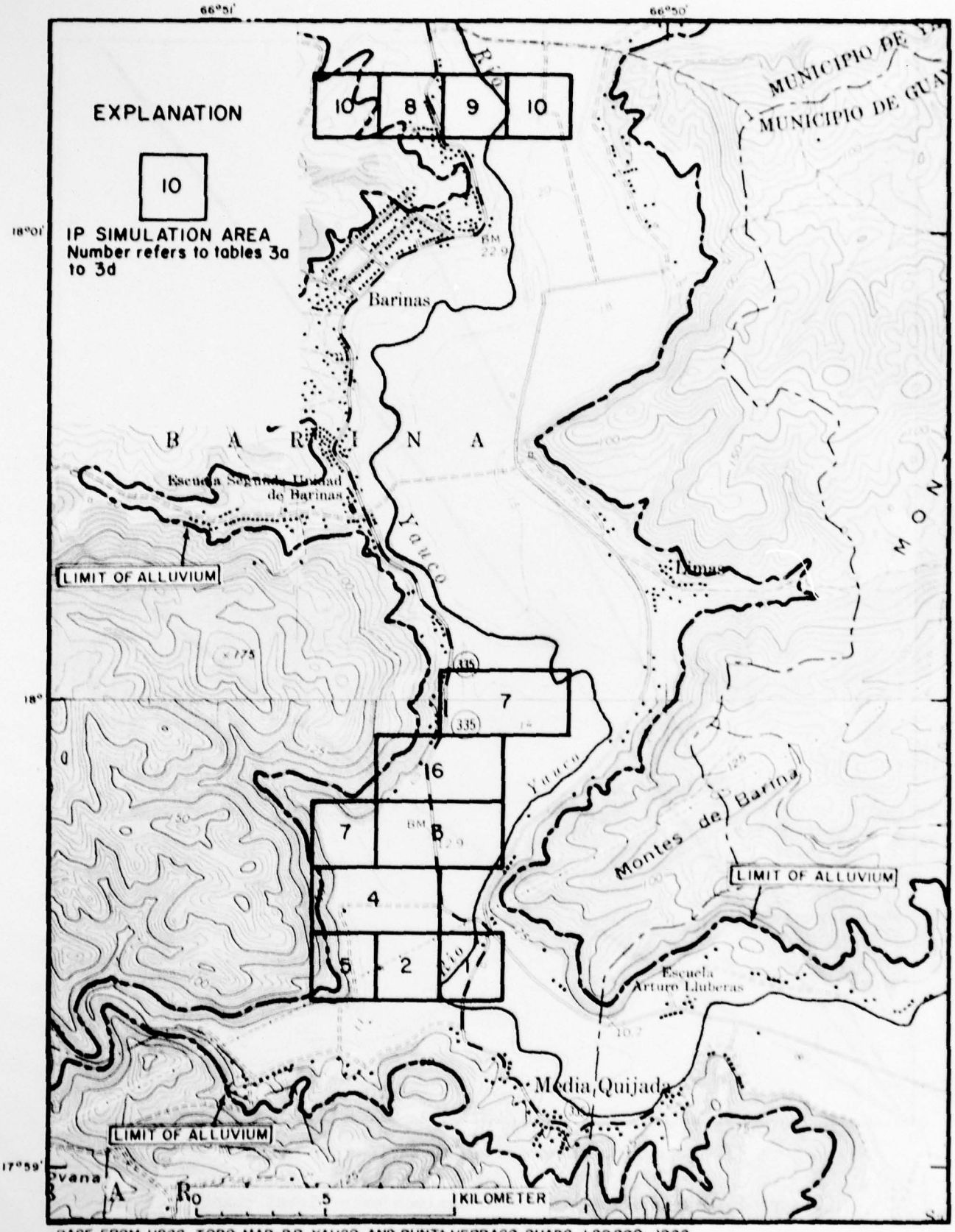
Infiltration-percolation simulations.--Sixteen high-rate infiltration-percolation (IP) simulations were run on the model. See figure 10 for the location of these tests. Thirteen of the tests were performed in the lower part of the valley near lat 17°59'22" to 17°59'38"N and long 66°50'22" to 66°50'27"W for a simulated period of 35 days. The maximum water-level change for these tests is listed in tables 3a through 3c. Table 3a gives results for tests run covering 16 acres; similarly tables 3b and 3c give results for tests covering 32 acres and 64 acres, respectively. Two other tests covering 128 (2, 3, 4, 5, and 6 on fig. 10) and 192 (1 through 7, fig. 10) acres in the same general area, resulted in maximum water-level changes of 42 ft for 7 Mgal/d applied and 34 ft for 9 Mgal/d applied, respectively.

Figure 11 is a graphic presentation of the data in tables 3a, b, and c; all the curves are plotted as second degree curves, although the curves could just as well be linear. The water-level change can be described



BASE FROM USGS TOPO MAP-P.R. YAUCO AND PUNTA VERRACO QUADS. 1:20,000, 1966

Figure 9.--Water-level changes resulting from simulated irrigation with 12 million gallons per day for 1 year in the Yauco Valley.



BASE FROM USGS TOPO MAP-P.R. YAUCO AND PUNTA VERRACO QUADS. 1:20,000, 1966

Figure 10.--Location of infiltration-percolation simulation sites in the Yauco Valley.

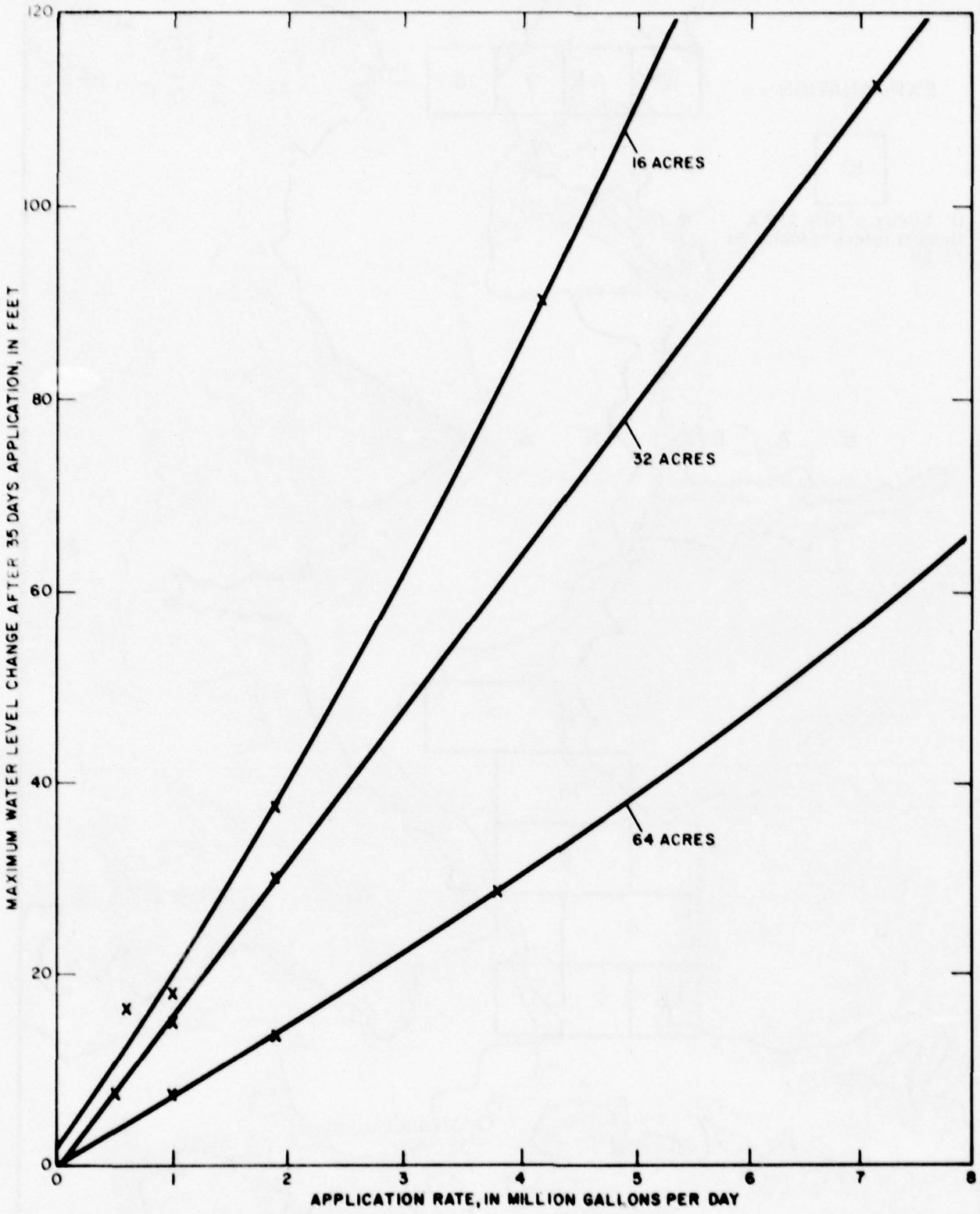


Figure 11.--Relationship between maximum water-level change, application rate, and area in Infiltration-Percolation simulations for 35 days in the lower Yauco Valley.

Table 3a.--Maximum water-level change resulting from high-rate infiltration in the Yauco Valley after 35 days on 16 acres.

Amount applied, Mgal/d	Recharge, Mgal/d	Maximum water-level rise, ft	Location, see figure 10
1	0.3	10	1
1.6	.5	11	1
3.2	1.0	24	1
7	2.1	[1]52	1

Table 3b.--Maximum water-level change resulting from high-rate infiltration in the Yauco Valley after 35 days on 32 acres.

Amount applied, Mgal/d	Recharge, Mgal/d	Maximum water-level rise, ft	Location, see figure 10
0.8	0.2	6.9	1, 2
1.6	.5	14	1, 2
2.0	.6	16.7	3
3.2	1.0	29	1, 2
12	3.6	[1]105	1, 2

Table 3c.--Maximum water-level change resulting from high-rate infiltration in the Yauco Valley after 35 days on 64 acres.

Amount applied, Mgal/d	Recharge, Mgal/d	Maximum water-level rise, ft	Location, see figure 10
1.6	0.5	9.4	1, 2, 4
3.2	1.0	17	1, 2, 4
4.0	1.2	[1]33	3, 4
6.4	1.9	[1]35	1, 2, 4

Table 3d.--Maximum water-level change resulting from high-rate infiltration (4.2 Mgal/d) over varying areas after 1 year.

Area, acres	Maximum water-level rise, ft	Location, see figure 10
16	[1]40	8
32	33	8, 9
64	29	8, 9, 10

[1] Waterlogging outside of the plot area would occur.

mathematically for these tests as:

$$y_{16} = 1.6 + 17.6X + .8X^2$$

$$y_{32} = -.3 + 15.8X - .03X^2$$

and $$y_{64} = .1 + 6.9X + .1X^2;$$

where y_{16}, y_{32} and y_{64} are the 35-day maximum water-level rises for application areas of 16 acres, 32 acres, and 64 acres, respectively; and X is the application rate in Mgal/d.

Three high-rate IP simulations located at 8, 9, and 10 on figure 10, were made in the upper valley. These tests were simulated for 1 year and were all made with the same application rate (4.2 Mgal/d) but the area of application was varied (16, 32, and 64 acres). The results of these tests are presented in figures 12, 13, and 14, and the maximum water-level changes are listed in table 3d.

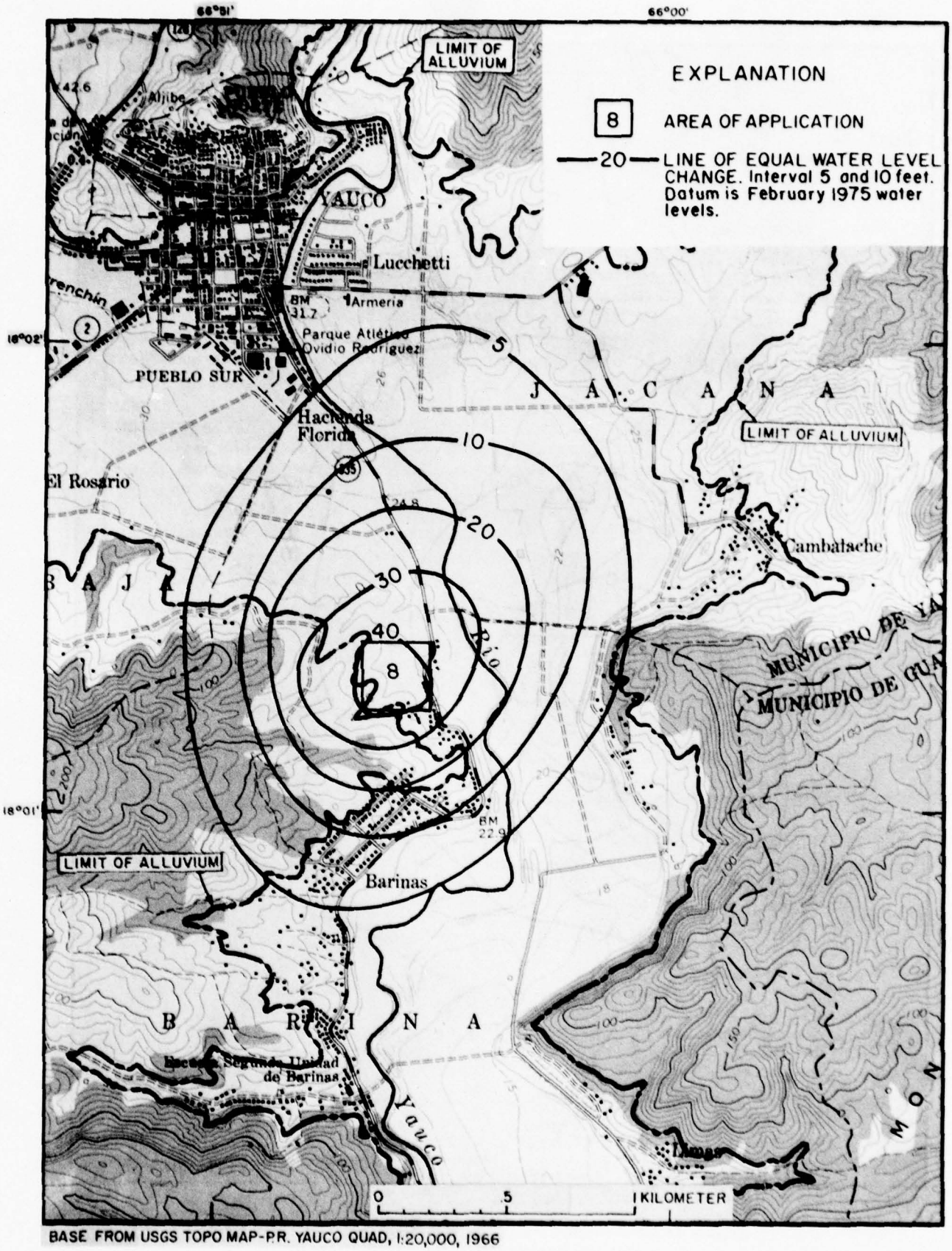
Based on the water-level changes and the thickness of the unsaturated zone, 4.2 Mgal/d could be applied on 32 acres at this site in the upper valley for most of the year. During wet weather, applications would have to be suspended. Although the maximum water-level change for an area of 64 acres is less, the areal pattern of application would have to be changed before this amount could be applied. The pattern used in the simulation extends too far east and the water-level rise here was greater than the thickness of the unsaturated zone.

There is not a significant difference between the water-level changes in these experiments because the water must move away from the site radially. Increasing the area by a factor of 2 increases the perimeter of the area by a factor of 1.5 or less.

If infiltration basins were set in small plots at long distances from each other they likely would be more efficient but probably would cost more because of the distribution problem.

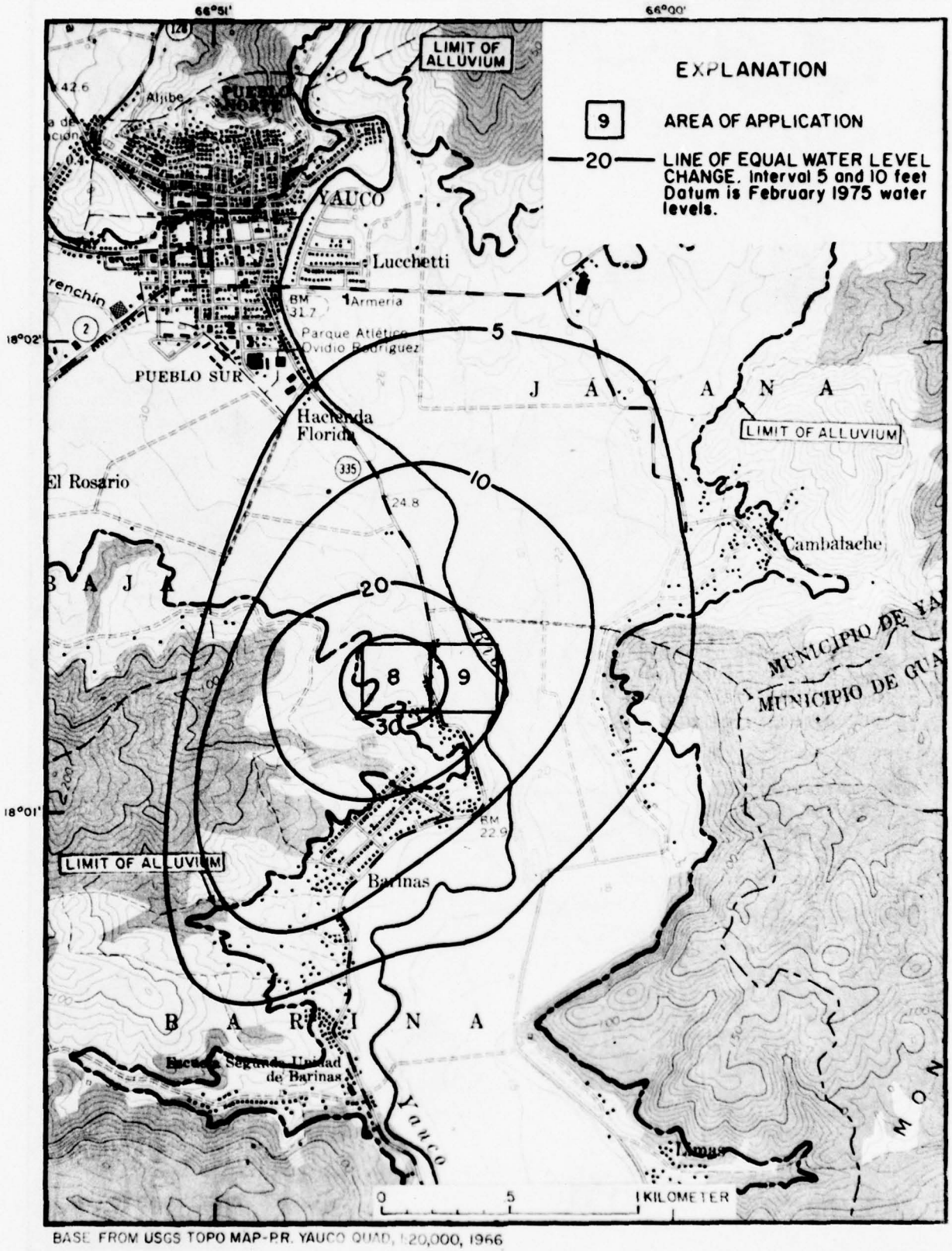
Río Guayanilla Valley

In contrast to the Río Yauco Valley, the Guayanilla Valley is wide compared to its length and the coastal plain is the dominant feature. The alluvium consists of much the same material as in the Yauco Valley and ranges from zero at the foothills to more than 100 ft thick in the lower part of the valley. The aquifer extends about 2 1/2 mi in a north-northwesterly direction from Bahía de Guayanilla. It is about 2 mi wide near Guayanilla and less than a third of a mile wide at the head of the valley.



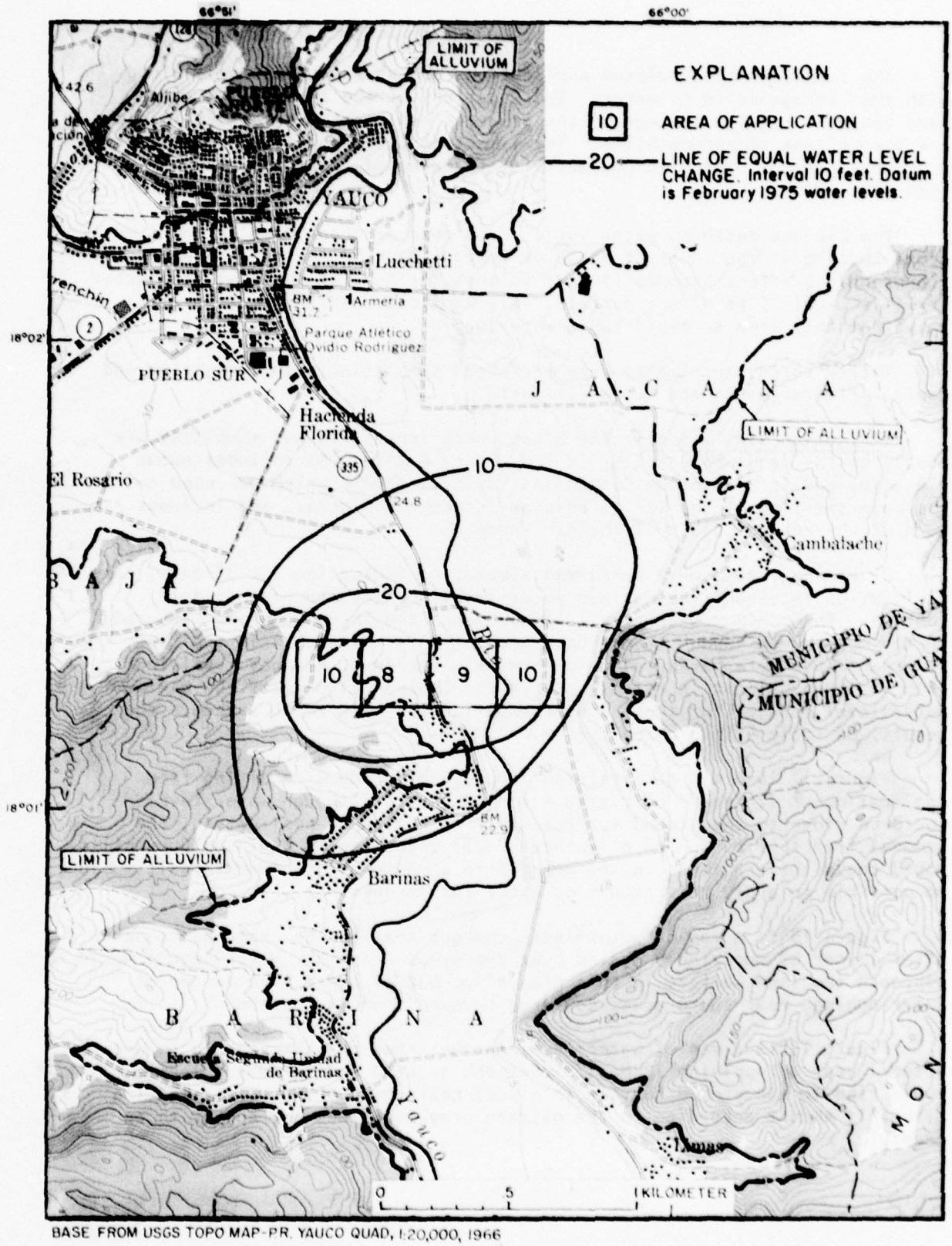
BASE FROM USGS TOPO MAP-P.R. YAUCO QUAD, 1:20,000, 1966

Figure 12.--Water-level changes in the Yauco area resulting from infiltration-percolation simulations of 4.2 million gallons per day applied over 16 acres.



BASE FROM USGS TOPO MAP-P.R. YAUCO QUAD, 1:20,000, 1966

Figure 13.--Water-level changes in the Yauco area resulting from infiltration-percolation simulations of of 4.2 million gallons per day applied over 32 acres.



BASE FROM USGS TOPO MAP-PR, YAUCO QUAD, 1:20,000, 1966

Figure 14.--Water-level changes in the Yauco area resulting from infiltration-percolation simulations of 4.2 million gallons per day applied over 64 acres.

The locations of simulated applications are shown on figure 15 along with the average depth to water. The locations of the application sites were chosen to take advantage of the greatest depth to water, which is along the base of the limestone hills. The limestone along the flanks of the hills possesses greater hydraulic conductivity than the adjacent alluvium (Bennett, 1976).

The average depth to water varies from greater than 30 ft in the limestone to zero at the shore of Bahía de Guayanilla. On the coastal plain the topographic gradient becomes flatter so that for most of the plain the water level is within 5 ft of the surface. All applications should be located away from this area to avoid rapid waterlogging.

Thirty-three experiments were performed simulating both irrigation and rapid infiltration in the Guayanilla area.

Irrigation simulations.--The areas where irrigation was simulated are mostly on the land where relief is low. Area A (fig. 15) includes about 830 acres and is all in the Guayanilla Valley. Area B which was used to increase the size of the irrigated area is about 960 acres, and includes much of the coastal plain of the Río Yauco.

Nine experiments were performed simulating irrigation for 35 days. The application rates and the maximum water-level changes are presented in table 4. The maximum water-level change means the largest change measured on the model even though it may have been at only one node. In addition, 11 experiments were performed to determine water-level changes resulting from various application rates for 1 year. Table 4 also lists the maximum water-level changes for these longer experiments. Figure 16 presents the results of table 4 in a graphic form.

Figure 17 is a map of simulated water-level changes resulting from application of 12 Mgal/d over area A for 35 days. Although water levels would be close to the ground surface under this plan of application, the removal from application of a few acres near the shore of Bahía de Guayanilla would cause the gradients in the near shore area to become lower and it would be possible to apply this amount of water for 35 days.

Figure 18 is a map of water-level changes that can be expected to occur after 1 year of applying 9 Mgal/d over the areas A and B. Water levels would approach the land surface in this plan also, but if there were danger of waterlogging, near-shore areas could be removed from irrigation.

Figure 19 is a map of water-level changes that can be expected to occur after 1 year of applying 12 Mgal/d over the areas A and B. Water levels would rise to the ground surface in places near the Río Yauco. Irrigating with this amount according to the pattern presented does not appear to be feasible.

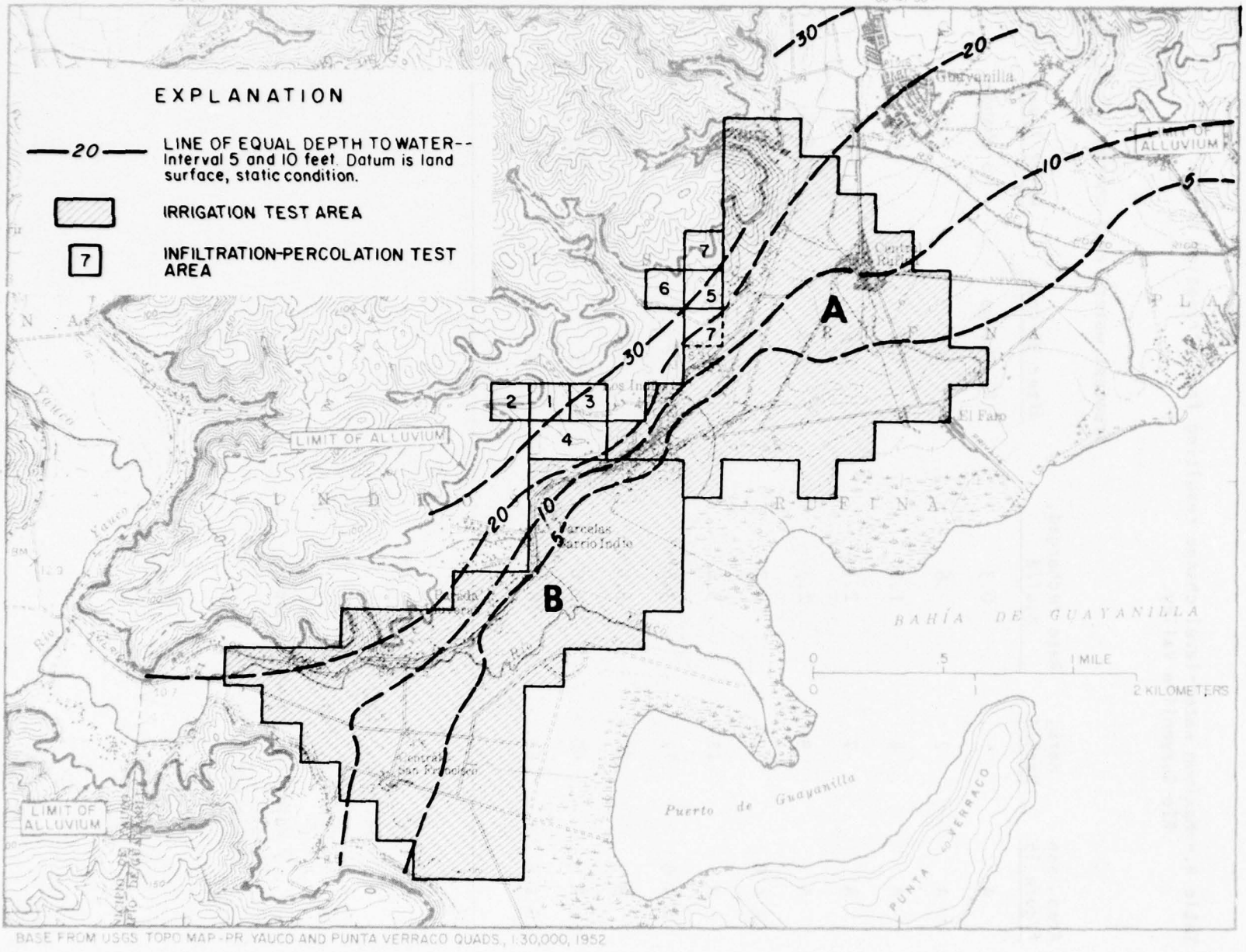


Figure 15.--Depth to water and location of simulated recharge applications in the Guayanilla area.

Table 4.--Maximum water-level change resulting from irrigation in the Río Guayanilla Valley.

Area, see figure 15	Rate, Mgal/d	Rate recharged, Mgal/d	Greatest water-level change, in ft	
			After 35 days	After 1 year
A	1	0.3	No change	No change
A	2	.6	0.8	2.2
A	4	1.2	1.2	4.5
A	7	2.1	2.4	6.8
A	9	2.7	2.9	9.0
A & B	9	2.7	--	[1] 3.7
A	12	3.6	[2] 4.1	[3] 14
A & B	12	3.6	--	[4] 4.9
A	20	6.0	[3] 6.6	[3] 20
A	40	12.0	[3] 15	[3] 39
A & B	60	18.0	[3] 14	[3] 33

[1] See map, fig. 18.

[2] See map, fig. 17.

[3] Waterlogging would occur.

[4] See map, fig. 19.

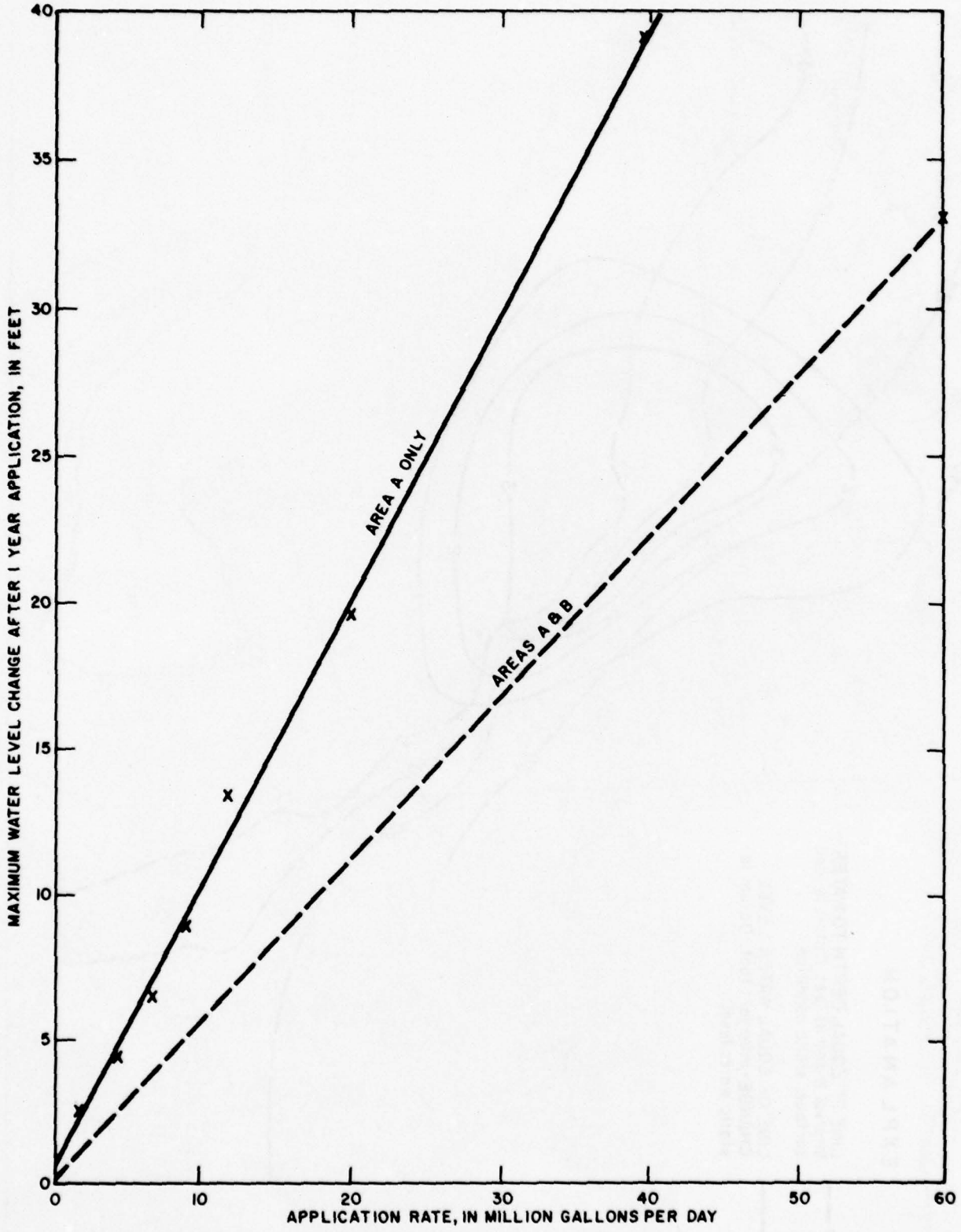


Figure 16.--Relationship between, application rate, and area of irrigation and maximum water-level change after 1 year in the Guayanilla Valley.

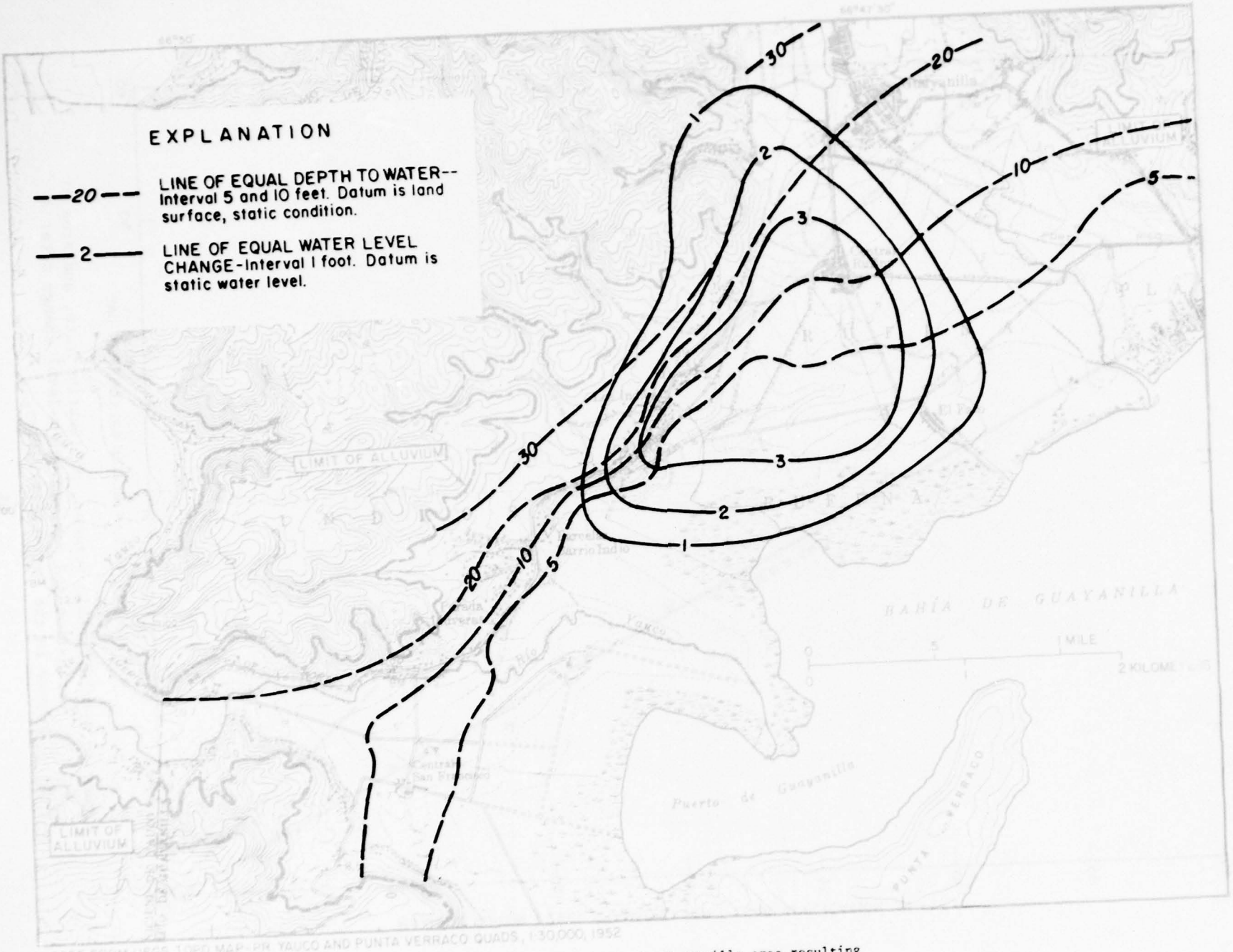


Figure 17.--Water-level changes in the Guayanilla area resulting from the simulated irrigation of area A for 35 days at a rate of 12 million gallons per day.

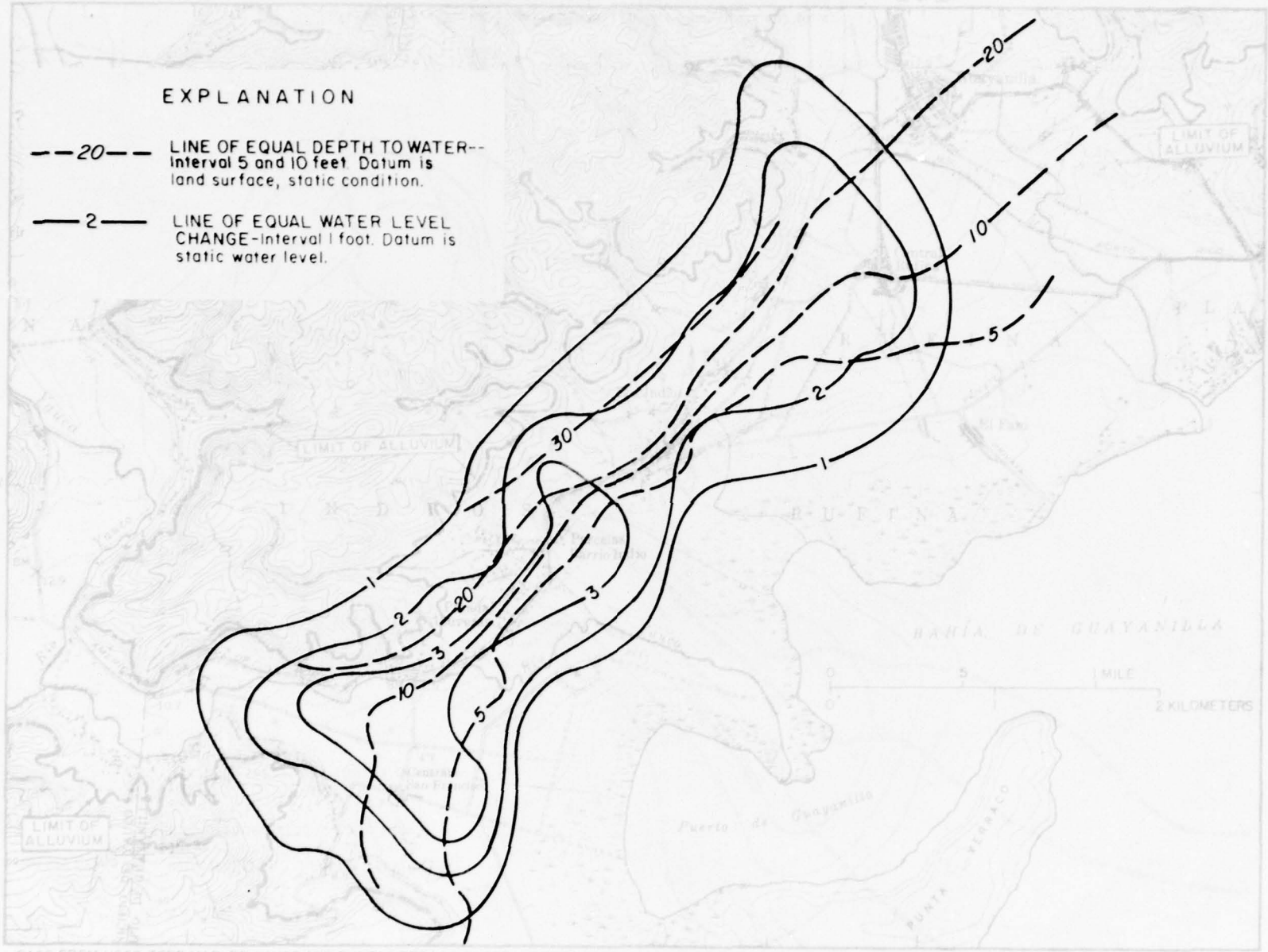


Figure 18.--Water-level changes in the Guayanilla area resulting from the simulated irrigation of areas A and B for 1 year at a rate of 9 million gallons per day.

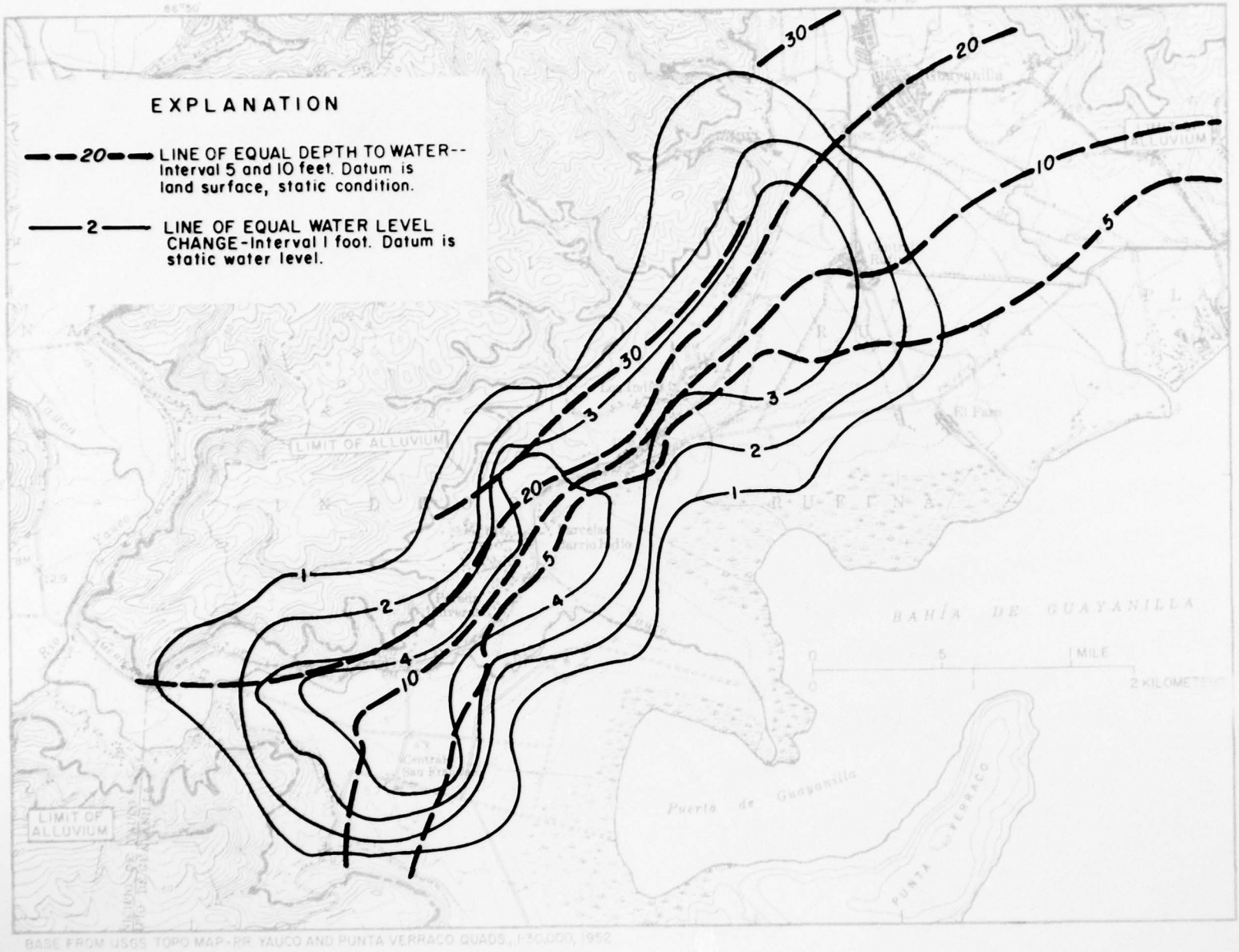


Figure 19.--Water-level changes in the Guayanilla area resulting from the simulated irrigation of areas A and B for 1 year at a rate of 12 million gallons per day.

Infiltration-percolation simulations.--Infiltration-percolation simulation was performed in two areas with different sized plots involved in each area. The locations and orientation of the plots are indicated on figure 15. Experiments were performed as described in table 5. Figure 20 is a graph of the data for the upper site from table 5.

Water-level rise decreased as the area was increased when application rates were equal, but the decreases were not linear. For example, at the upper site an application rate of 3 Mgal/d, doubling the area from 16 to 32 acres produced a 30 percent less rise (20 ft versus 14 ft). However, doubling the area from 32 to 64 acres produced a 46 percent less rise (14 ft versus 7.8 ft). At an application rate of 7 to 7.5 Mgal/d, increasing the area four times, from 16 to 64 acres, produced a 61 percent less rise (48 ft versus 18 ft).

One IP test was performed for a 1-year period in the Guayanilla area. The amount applied was 1 Mgal/d over 32 acres located in the same place as the 32 acres in the 35-day test (sites 5, 6 on fig. 15). The maximum water-level change was 5.8 ft. A similar IP test was performed to estimate the water-level change due to 3 Mgal/d spread on the same area for a year. The maximum water-level change in this case was 18 ft or 1.3 times the change after 35 days. The distribution of the water-level changes is shown in figure 21.

Río Tallaboa Valley

The Tallaboa Valley aquifer consists of alluvium in a valley between limestone hills. It is narrow compared with its length and extends 4.2 mi north from Bahía de Tallaboa. At the shoreline it is 2.7 mi wide but the coastal plain is quite limited. The aquifer covers an area of 6.8 sq mi. The alluvium varies in thickness from 0 to over 200 ft.

Each of the situations discussed in the following paragraphs is unique and can be utilized only as an exclusive method. Irrigation and high-rate infiltration cannot both be practiced at the rates stated without interfering with each other.

Irrigation simulations.--In the Tallaboa area 10 irrigation simulations were performed for a period of 35 days and 2 simulations for a 1-year period. In all simulations the area and location are the same and consist of 740 acres. Figure 22 shows the location of the irrigation simulation and the depth to water. Depth to water measurements south of 18°02'N were made in February 1975; the others were made at various earlier times, and it is not known whether all are static or if some are pumping levels. It is known, however, that many of these wells go dry in extremely dry periods.

Table 5.--Maximum water-level change resulting from high-rate infiltration in the Guayanilla area.

Amount, Mgal/d	Recharged Mgal/d	Area, acres	Maximum water-level change, ft	Location, see figure 15
		Lower Site		
1	0.9	16	16	1
5	4.5	48	[1]78	1, 2, 3
1	.9	64	12	1, 3, 4
		Upper Site		
1	0.9	16	7.6	5
3	2.7	16	20	5
5	4.5	16	[1]34	5
7.5	6.8	16	[1]48	5
3	2.7	32	14	5, 6
7	6.3	32	[1]40	5, 6
10	9.0	32	[1]47	5, 6
3	2.7	64	7.8	5, 6, 7
7	6.3	64	[1]18	5, 6, 7
10	9.0	64	[1]25	5, 6, 7
15	13.5	64	[1]42	5, 6, 7
20	18.0	64	[1]58	5, 6, 7

[1]Waterlogging outside of the plot area would occur.

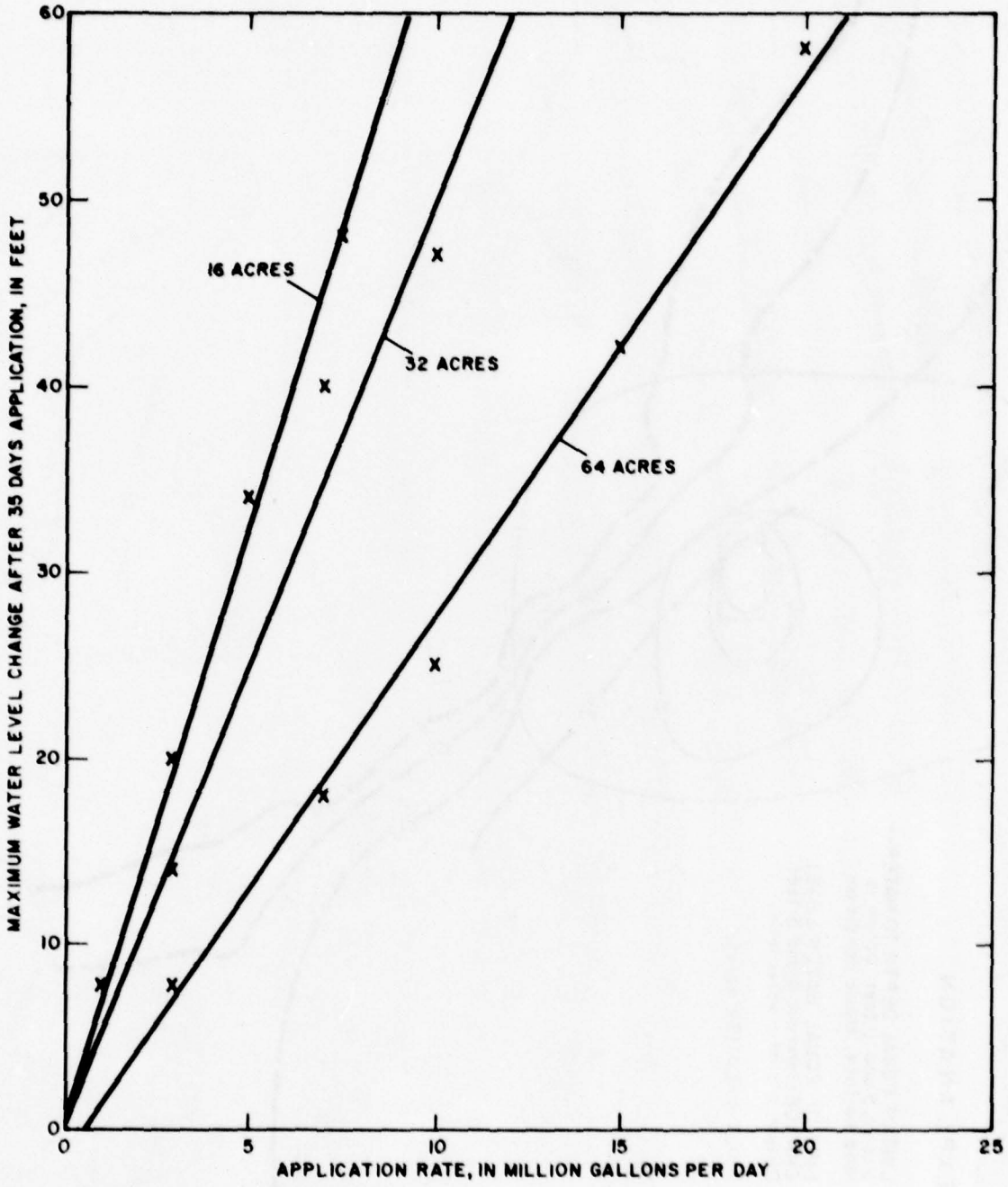


Figure 20.--Relationship between maximum water-level change, application rate, and area in infiltration-percolation simulations in the Guayanilla Valley.

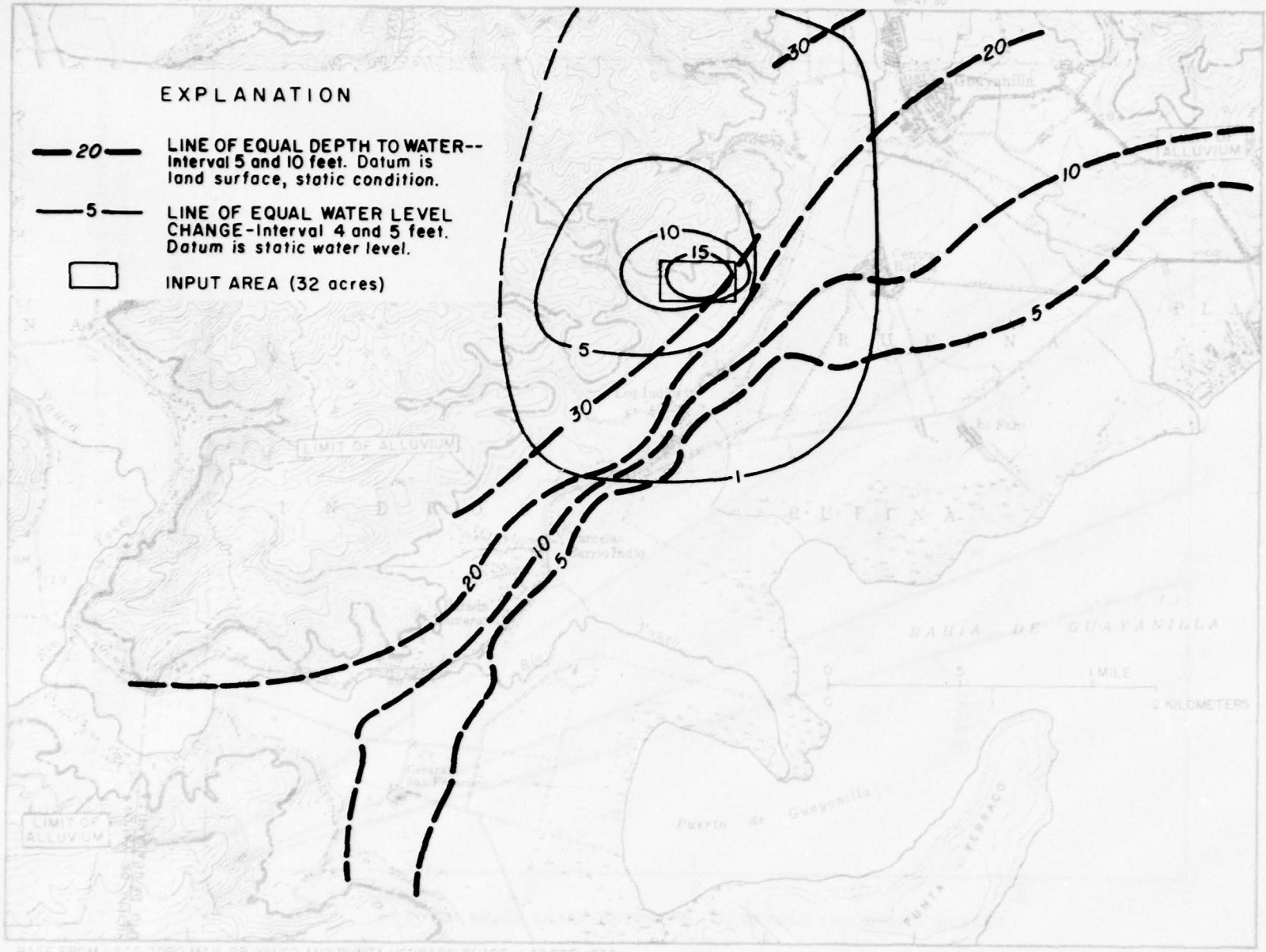


Figure 21.--Water-level changes resulting from infiltration-percolation simulations with 3 million gallons per day over 32 acres for 1 year in the Guayanilla Valley.

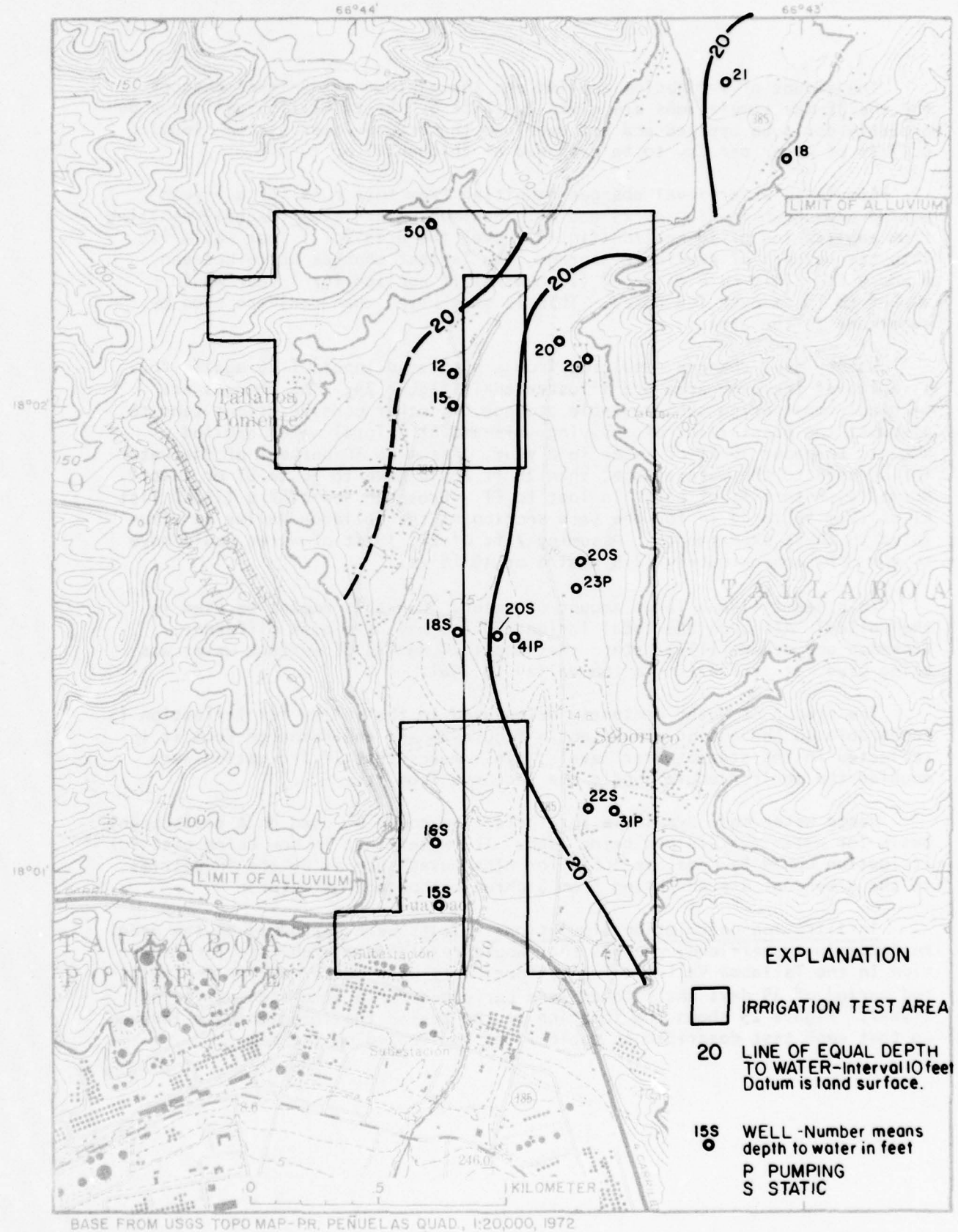


Figure 22.--Depth to water and location of irrigation simulations in the Tallaboa Valley.

The amount of irrigation applied and the maximum water-level changes for the 35-day simulations are given in table 6. Sixty million gallons a day probably could be applied and not overload the ground-water system, leaving 0.17 ft of water per day to be disposed of through ET or runoff.

Simulated water-level changes resulting from test runs for a 1-year period are shown in figures 23 and 24. Maximum water-level changes resulting from application of 10 Mgal/d (fig. 23) over the area for 1 year would fit into the pattern of available storage, the largest changes being between 8 and 9 ft. This rate of water (10 Mgal/d) if applied for 1 year would amount to 15 ft over 740 acres. This is more water than could be used by sugarcane in the area.

Water-level changes resulting from a simulated input of 25 Mgal/d for 1 year over the same area are illustrated in figure 24. The changes are marginal considering the available storage but other considerations tend to discount the possibility of applying this amount. Total water applied amounts to about 38 ft of water in a year. Assuming 30 percent of the water infiltrated to the water table, then 26 ft would have to go to ET or runoff. Normally, 4 to 6 ft of water is lost to ET. Grossman and others (1972) list ET of from 45 to 88 in for the same section of the Tallaboa Valley as simulated in these experiments. Assuming 7 ft of ET, 19 ft of water would have to run off, approximately 12.5 Mgal/d or 19 ft^3/s.

This seems like a large amount of water. Can this amount be used in the valley? Although the total irrigated area may have been different, Grossman and others (1972) state that about 20 Mgal/d of surface water was being used for irrigation in the valley in 1961.

The amount of water presently being used in the valley for irrigation is comparable to the amount simulated in figure 24 and the recharge from it is reflected in the static water levels. This means that if irrigation were doubled the aquifer could handle the recharge from it.

Waste water made available for irrigation could be used on a replacement basis for water that is now being used. The water that is now being used for irrigation could be made available for other uses such as by the industries in the area that are suffering from a chronic shortage of water.

Infiltration-percolation simulations.--Tests were performed on the model to determine water-level changes that would result from high-rate infiltration in the Tallaboa Valley. Twenty-four tests were performed for a simulated period of 35 days and 4 tests were performed for a simulated period of 1 year. Figure 25 shows the location of the tests; the locations are indexed so that each test described in table 7 can be located on the map.

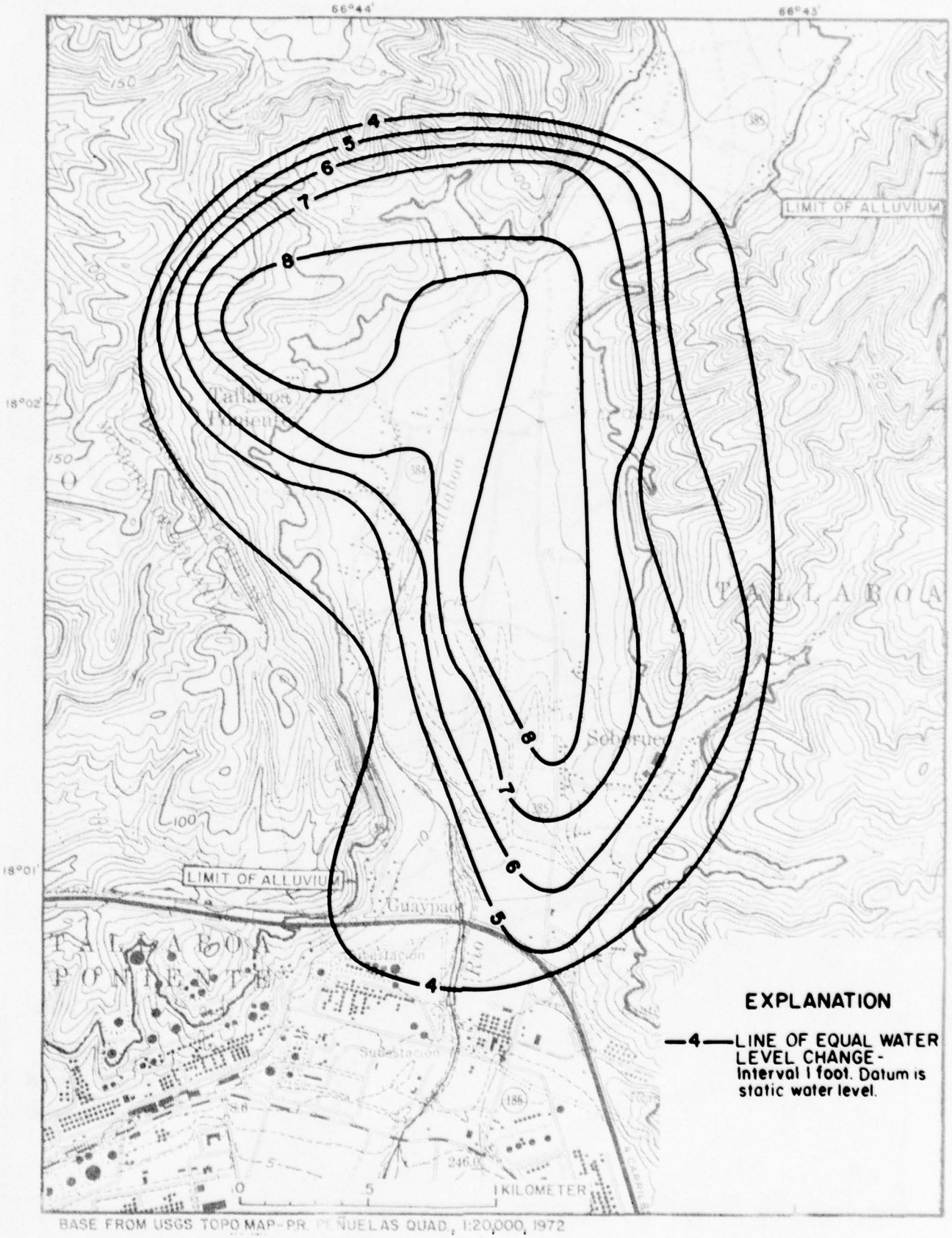


Figure 23.—Water-level changes resulting from simulated irrigation with 10 million gallons per day for 1 year in the Tallaboa Valley.

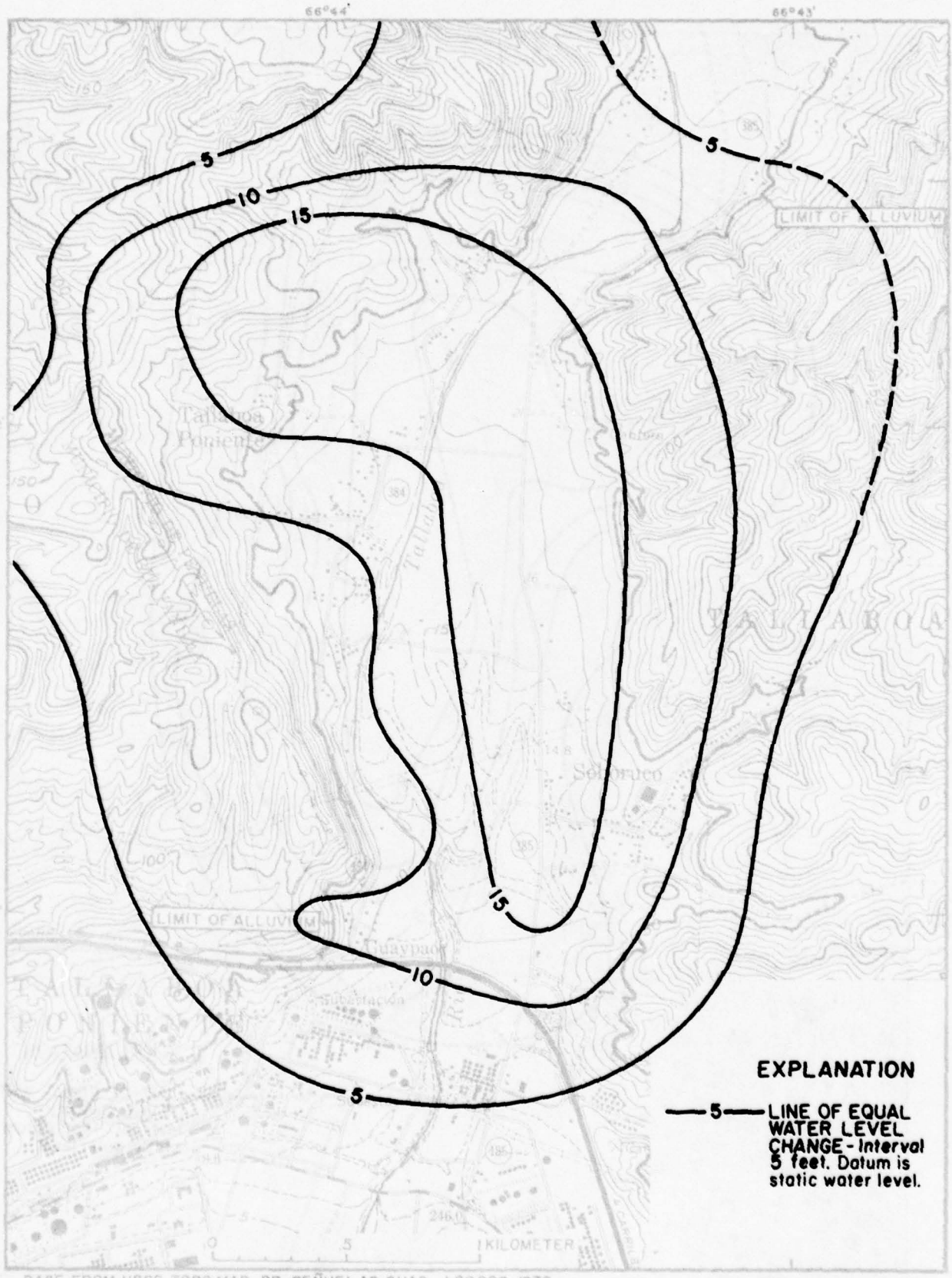


Figure 24.--Water-level changes resulting from simulated irrigation with 25 million gallons per day for 1 year in the Tallaboa Valley.

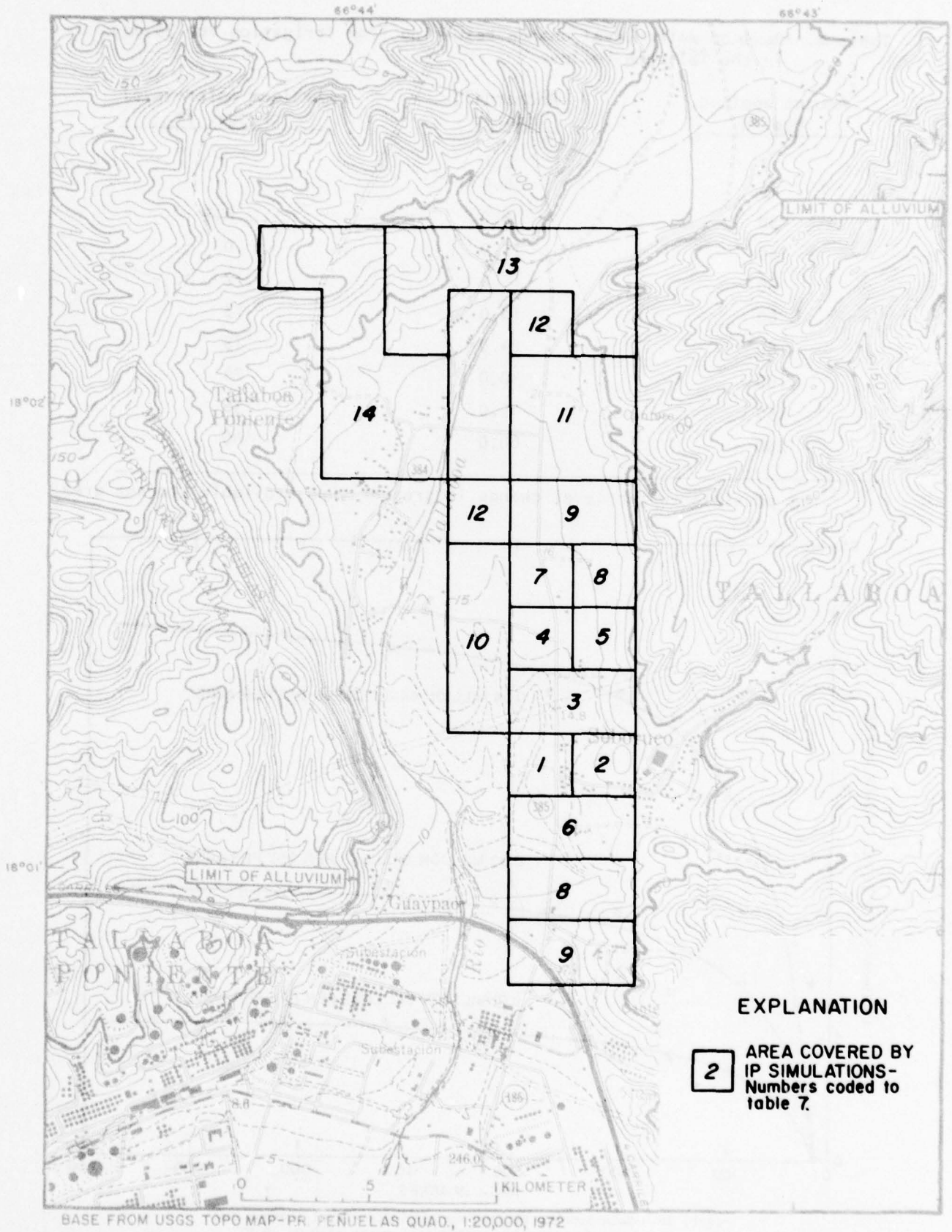


Figure 25.--Location of infiltration-percolation simulations in the Tallaboa Valley.

Table 6.--Maximum water-level change resulting from irrigation for 35 days in the Tallaboa Valley.

Amount applied, Mgal/d	Recharged, Mgal/d	Maximum water-level change, ft
7	2.1	-
15	4.5	-
30	9.0	6.9
40	12.0	10
50	15.0	12
60	18.0	13
80	24.0	[1]19
100	30.0	[1]24
150	45.0	[1]36
200	60.0	[1]46

[1] Not possible--water-level change is greater than available storage area.

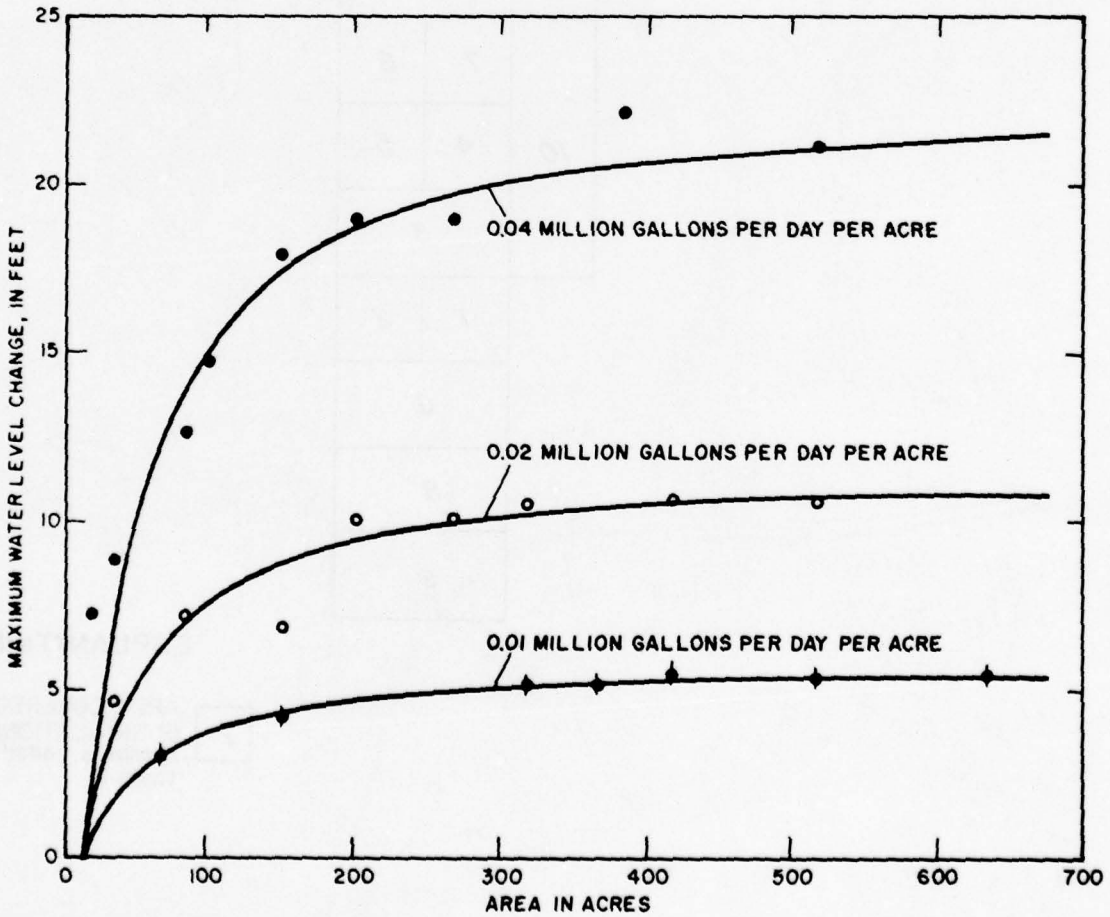


Figure 26.--Relationship between maximum water-level changes and area for specific application rates of 0.04, 0.02, and 0.01 million gallons per day per acre for 35 days in the Tallaboa Valley.

The 35-day simulations were divided into 3 series in which each test had the same loading rates, which were 0.4, 0.2 and 0.1 Mgal/d per acre. Results were such that none of the tests would have been feasible because simulated water-level changes exceeded the measured depth to water in the valley. By reducing the application rates it was noted that for large areas 0.04 Mgal/d was the limit that could be applied for 35 days. Even at this rate some areas outside of the flooded plots would become waterlogged. Table 7 lists the maximum water-level changes that would occur if water were applied at rates of 0.04, 0.02, and 0.01 Mgal/d per acre. Figure 26 is a graph showing the effect on the maximum water-level changes of increasing the area and amount applied for each of these series.

The curves for the 3 sets of data are defined by the equation $y = Ae^{(1-\frac{40}{x+1})}$, where y is the maximum water-level change, x is the area and A is determined by the rate of application. A is 8.5, 4.3 and 2.2 for rates of application of 0.04, 0.02 and 0.01 (Mgal/d)/acre, respectively.

Table 8 contains a list of the maximum water-level changes resulting from high rate infiltration for a year. The tests were performed at a simulated rate of 2.75 Mgal/d and covered areas of 16, 32, 80, and 144 acres.

Figure 27 shows water-level changes that occurred as a result of the simulated application of 2.75 Mgal/d over 16 acres for a year.

The simulated water-level changes resulting from the application of 2.75 Mgal/d over 144 acres for 1 year are shown in figure 28. Even though the area is increased by a factor of 9 over the test shown in figure 27, the maximum water-level changes are approximately one-half that for a smaller area. This indicates that for longer periods, as the storage is satisfied, and the flow is approaching steady state, an increase in area is not an effective means of increasing the amount of infiltration.

Table 8.--Maximum water-level change resulting from high-rate infiltration in the Tallaboa area after 1 year.

Area	Maximum water-level change, ft	Location, see figure 25	Rate, Mgal/d per acre	Recharge, ft/day
16	31 [1]	1	0.17	0.47
32	30 [1]	1, 2	.09	.25
80	22	1-4 inclusive	.03	.08
144	14	1-7 inclusive	.02	.06

[1]Waterlogging outside of application area.

Table 7.--Maximum water-level change resulting from high-rate infiltration in the Tallaboa Valley after 35 days.

Area, acres	Maximum water-level change, ft	Location[1], see figure 25	Rate, Mgal/d per acre	Recharge, ft/day
16	6.9	1	0.04	0.11
32	8.4	1, 2	.04	.11
80	12	1-4	.04	.11
96	14	1-5	.04	.11
128	17	1-6	.04	.11
144	17	1-7	.04	.11
192	18	1-8	.04	.11
256	18	1-9	.04	.11
368	21	1-11	.04	.11
496	20	1-13	.04	.11
32	4.4	1, 2	.02	.06
80	6.8	1-4	.02	.06
144	6.5	1-7	.02	.06
192	9.5	1-8	.02	.06
256	9.6	1-9	.02	.06
304	10	1-10	.02	.06
400	10	1-12	.02	.06
496	10	1-13	.02	.06
64	2.9	1-3	.01	.03
144	4.0	1-7	.01	.03
304	4.9	1-10	.01	.03
400	5.2	1-12	.01	.03
496	5.0	1-13	.01	.03
608	5.1	1-14	.01	.03

[1] Where multiple locations are indicated the numbered areas are inclusive.



Figure 27.--Water-level changes resulting from the infiltration-percolation simulation with 2.75 million gallons per day over 16 acres for 1 year in the Tallaboa Valley.

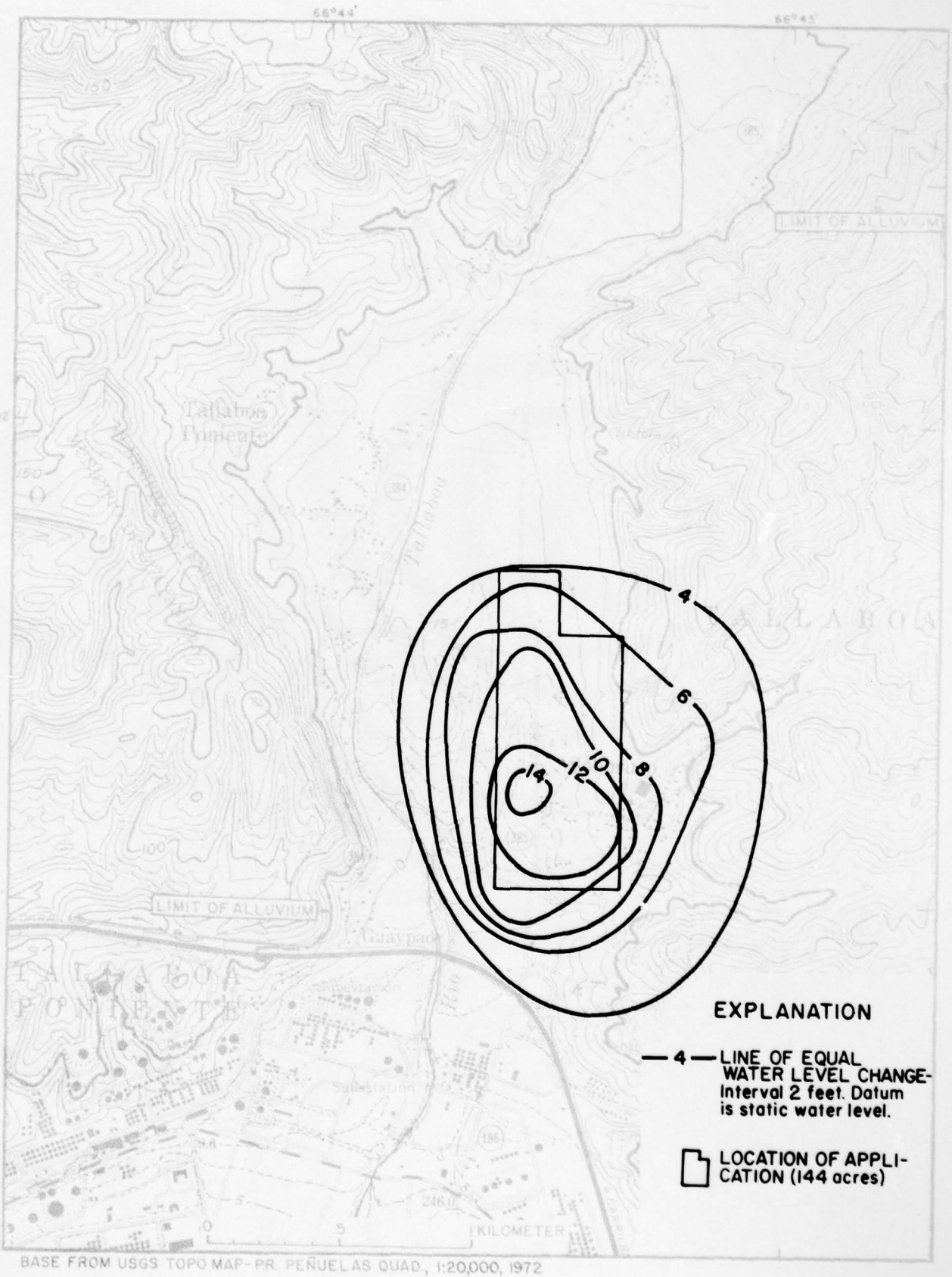


Figure 28.--Water-level changes resulting from the infiltration-percolation simulation with 2.75 million gallons per day over 144 acres for 1 year in the Tallaboa Valley.

Ponce Area

Three areas in the vicinity of Ponce were considered for experiments using the analog model. The first area considered was to the southwest of Ponce along the coast west of Playa de Ponce, adjacent to the sewage treatment plant. No experiments in this area were attempted, however, because this area is characterized by a high water table and swampland behind a 6- to 9-ft ridge. Only on the ridge would the depth to water be as much as 6 ft. If this area were used for disposal purposes, waste water would soon emerge in the swamp.

The other two areas considered in the vicinity of Ponce were in the valley of the Ríos Pastillo and Cañas, west of Ponce. The area of the alluvial plain here is 10.6 mi^2 (McClymonds, 1972). The two rivers flow in the mountains but lose all their water to the alluvium during dry seasons. When available, some water is diverted from the Río Cañas for irrigation. The alluvium has a hydraulic conductivity of less than 2 ft/d and a saturated thickness of less than 100 ft (Bennett, 1976).

Infiltration-percolation simulations.--Five high-rate infiltration tests were performed in the valley of the Ríos Cañas and Pastillo northwest of Ponce. Table 9 contains a list of the experiments indicating the simulated application rate, area, and the water-level change due to the water application. Figure 29 is a map of the area, showing the experimental plots and the depth to water. The depths to water are taken from historical records and do not represent any special time of the year. The water-level changes were greater than available storage area at all application rates.

Table 9.--Maximum water-level change resulting from high-rate infiltration in the Cañas Pastillo Valley for 1 year.

Rate, Mgal/d	Area, acre	Specific rate, Mgal/d per acre	Recharge, ft/day	Maximum water level changes, ft	Location,[1] area number[2]
4.2	16	0.26	0.72	112	1
8.8	32	.28	.77	210	1, 2
4.2	32	.13	.36	98	1, 2
8.8	80	.11	.30	165	1-5
4.2	64	.07	.19	90	1-4

[1] Multiple site numbers indicate all sites within the range are included.

[2] See figure 29.

Note: All of these application rates would cause widespread waterlogging.

Deep-well injection.--Three experiments were performed to determine the effects of deep-well disposal in the area of the Ríos Cañas and Pastillo northwest of Ponce. There is no place within this area where the alluvium is greater than 100 ft thick. Simulation of deep-well injection was done in the alluvium and not in the limestone, because the limestone is very porous in this area and the injected waste would move very quickly through the formation with no filtering action.

The experiments were performed by injection (applying current) to the second layer of the model. This corresponds to a depth of 65 ft below the water table. Pressure changes in the second layer were recorded as well as those in the top layer. All values were recorded in feet. The simulated injection corresponded to 3, 6, and 12 Mgal/d.

Figures 30, 31, and 32 indicate the water-level changes that would occur in both the surface and deeper layers of the aquifer under the stated stress after 1 year. Pressure changes in the second layer were much greater and covered a larger area than those in the top layer. Only the changes in the surface layer are subject to the limits of the unsaturated thickness shown in figure 29.

Considering the results of these tests, it is possible to move 12 Mgal/d through the aquifer.

Central Mercedita Area

The area in which simulation tests were performed is roughly between the sugar processing plant, Central Mercedita, and the Río Jacaguas, and from lat 18°N, north to the outcrops of the limestone foothills that form the sides of the Río Inabón valley as it emerges from the foothills. The Ríos Inabón and Jacaguas flow through the test area, the Inabón bisecting the area and the Jacaguas flowing through the southeast corner of the irrigation test area. These rivers are dry most of the year, where they cross the area, having been depleted by natural recharge to the aquifer and diversions for irrigation.

The thickness of the saturated part of the alluvium varies in the area from over 300 ft in the south to about 50 ft where the Río Inabón emerges from the foothills (Bennett, 1976). Transmissivities in the area vary from 15,000 to 20,000 ft^2/d to 1000 ft^2/d, decreasing from south to north.

The locations of the IP and irrigation areas were determined by sewage treatment plant location and distribution convenience. However, water-level records indicate that the water levels are very close to the ground in the coastal areas and north to approximately lat 18°N. The coastal area is in sugar production only because of an extensive system of drainage canals. High-rate inflation percolation is not recommended in this area, and because

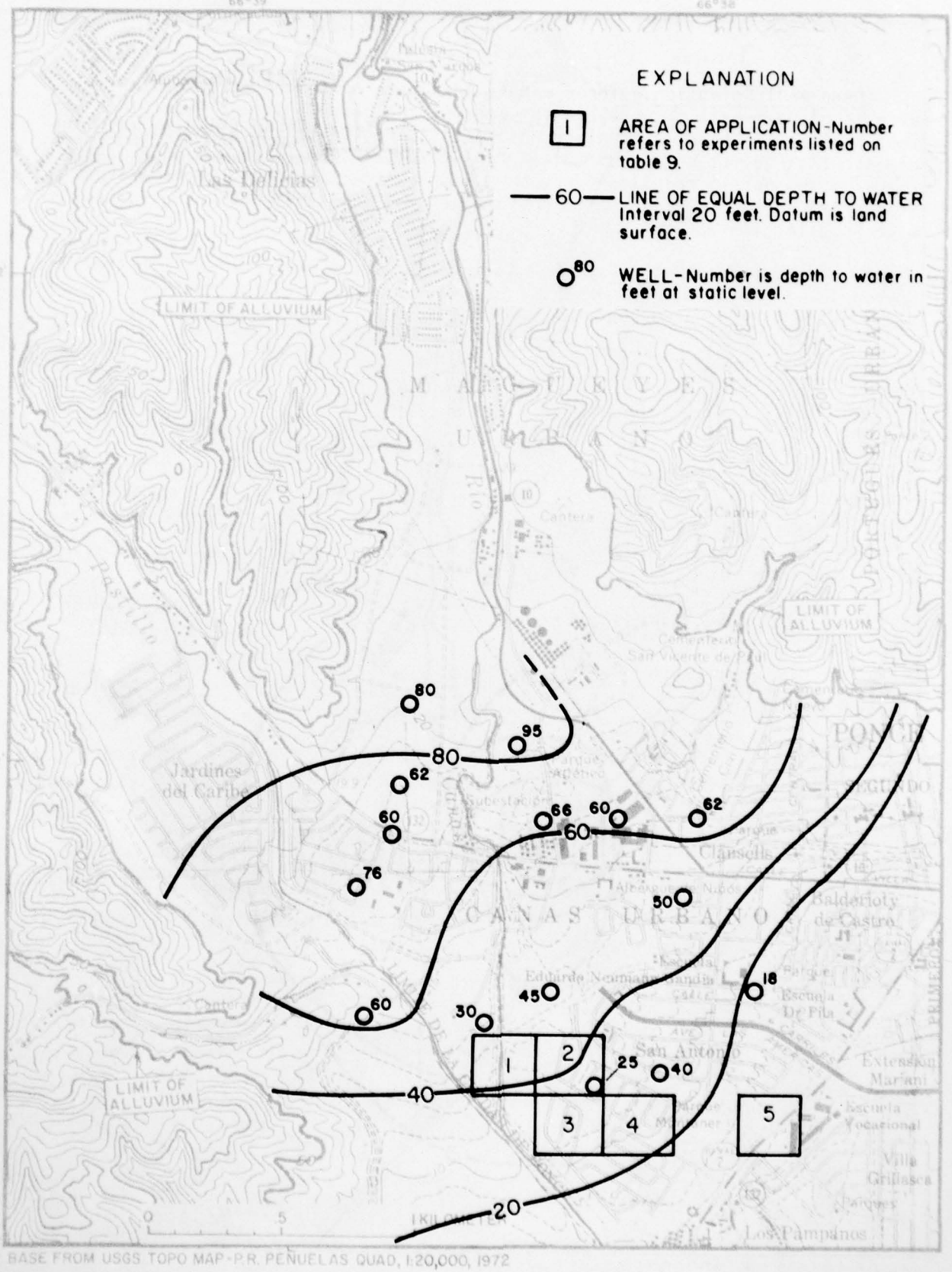
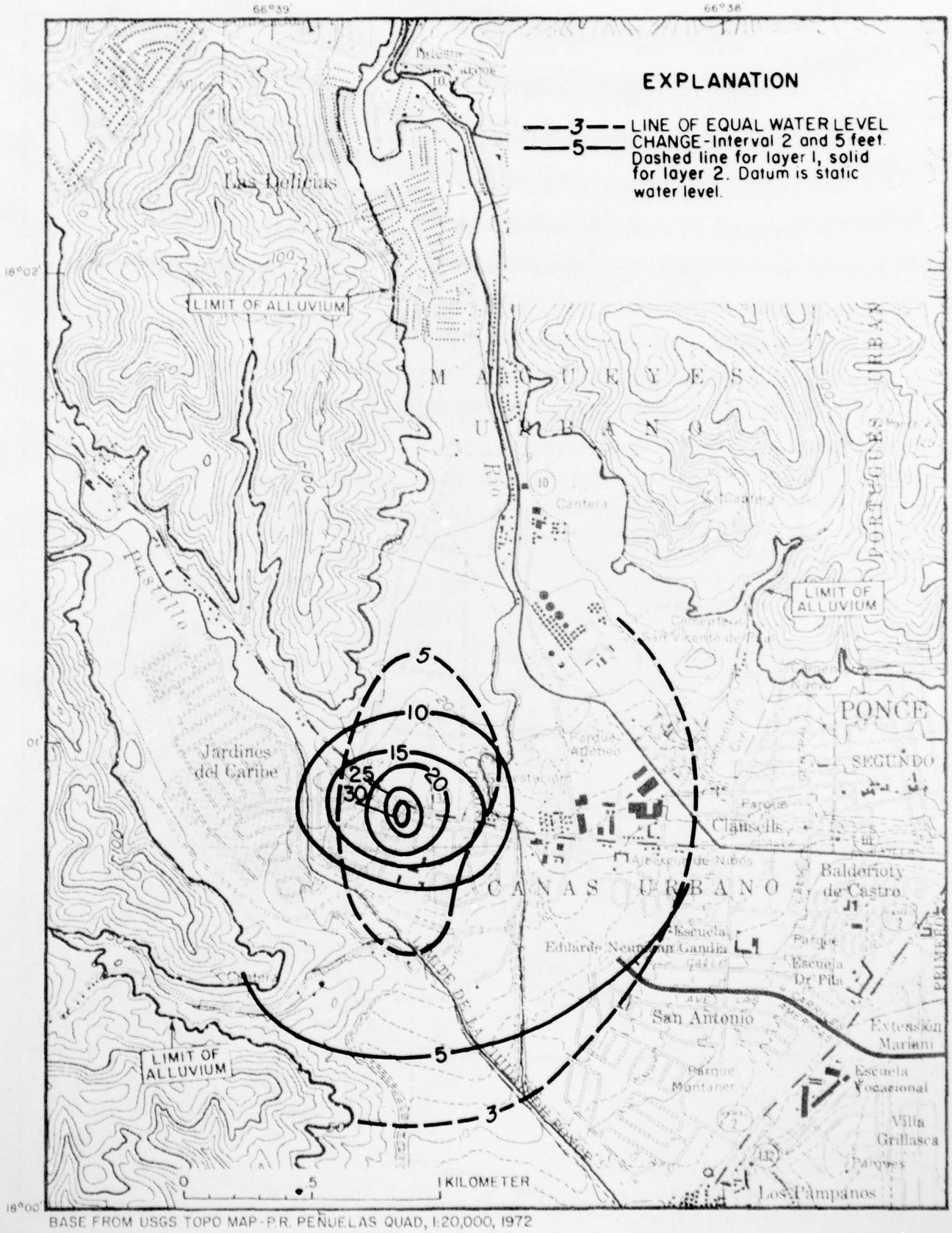


Figure 29.--Depth to water and location of infiltration-percolation simulation sites in the Ríos Cañas-Pastillo Valley area.



BASE FROM USGS TOPO MAP-P.R. PEÑUELAS QUAD, 1:20,000, 1972

Figure 30.--Water-level changes in the Ríos Cañas-Pastillo Valley area resulting from simulated deep-well injection with 3 million gallons per day for 1 year.

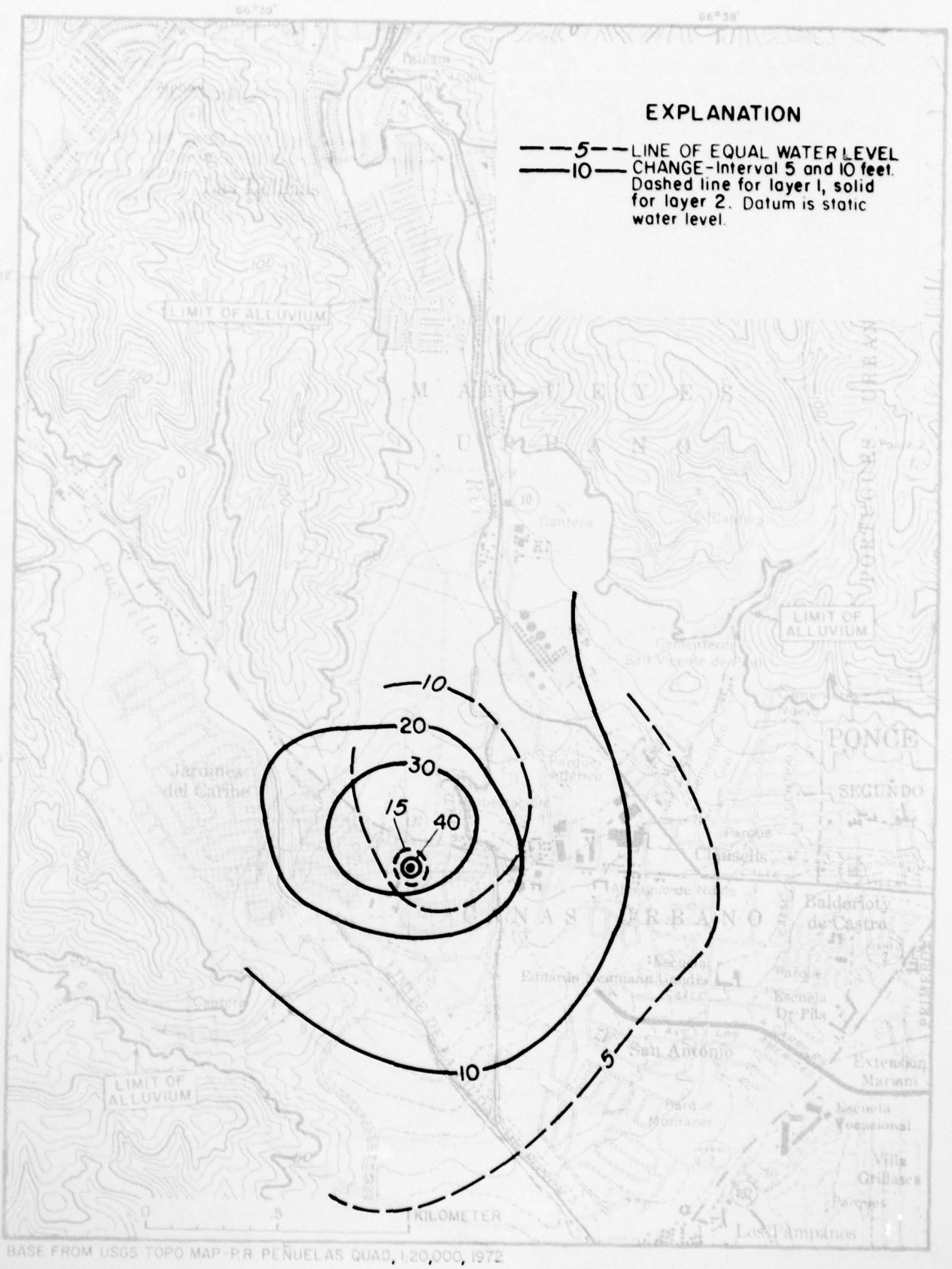


Figure 31.--Water-level changes in the Ríos-Cañas-Pastillo Valley area resulting from simulated deep-well injection with 6 million gallons per day for 1 year.

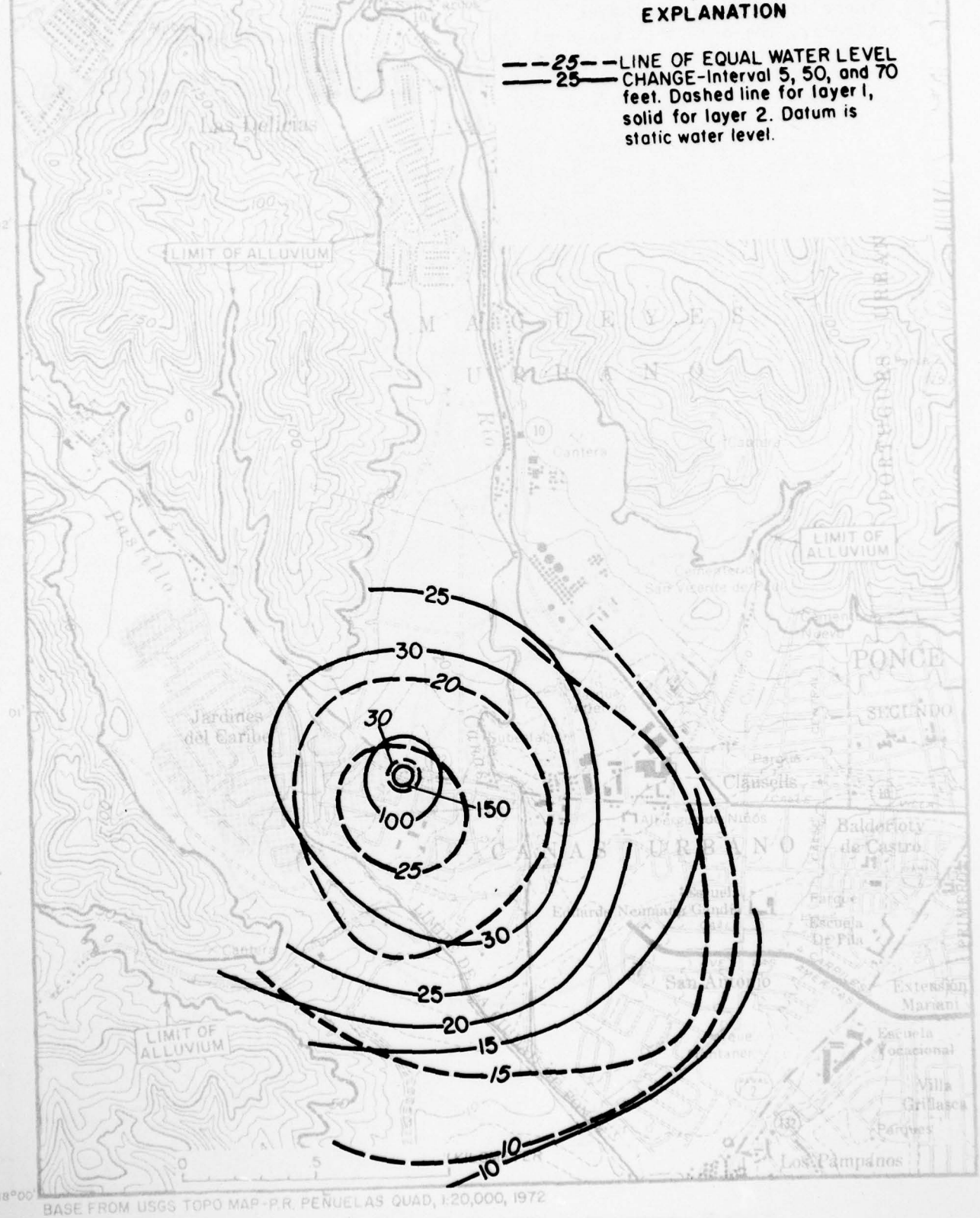


Figure 32.--Water-level changes in the Ríos-Cañas-Pastillo Valley area resulting from simulated deep-well injection with 12 million gallons per day for 1 year.

there is an excess of water, irrigation also would not be advisable. Consequently, the area that was used for the simulation exercises was north of lat 18°N and between Central Mercedita and the Río Jacaguas. Figure 33 is a map of the Mercedita area showing the location of the irrigation and IP simulations and the depth to water.

Irrigation simulations.--Irrigation in the Mercedita area was simulated by applying varying amounts of electric current to an area on the model that corresponds to approximately 3,000 acres. When 5 Mgal/d was applied for a simulated period of 35 days, changes over the entire area were 1.8 ft or less. At 10 Mgal/d for the same period, 3.3 ft was the maximum change. Figure 34 is a map of the area of irrigation and the water-level changes that would take place when 20 Mgal/d is applied for 35 days. The maximum change in water level is 6.7 ft and is limited in areal extent. The change in water level is greater at the southern limit of the irrigated area. This is very close to the area that is normally drained so that crops can grow. Irrigation should not be attempted closer to the drained area because of possible waterlogging of the soil.

Table 10 lists the maximum water-level changes that would occur after irrigating the area for 35 days and for 1 year, for various rates of application. About 40 Mgal/d could be applied for 35 days and about 30 Mgal/d for a year before waterlogging would occur in the area.

Changes in water level that would occur after 1 year of irrigation over the 3,000 acres with 20 Mgal/d are shown in figure 35. After the year, water levels would be between 5 and 8 ft below the land surface and approximately 25 percent of the water that recharged the aquifer would run off in the rivers; about 7.5 percent of the 20 Mgal/d.

Infiltration-percolation simulations.--High-rate IP was simulated in the Mercedita area. Three series of tests were performed using rates of application corresponding to 0.4, 0.2, and 0.1 Mgal/d per acre. Simulated water-level changes were so large that the analog model could no longer be considered an accurate representation of the system and the tests were considered to have no significance. The application rates were then reduced to 0.04, 0.02, and 0.01 Mgal/d per acre. Maximum water-level changes for these reduced applications are listed in table 11. All of these tests were for 35 days. The tests are indexed by number to their location shown on figure 33.

Four IP tests were performed for a simulated period of 1 year in the area. These tests indicated that large areas of land must be set aside for IP activities for rather small amounts of recharge. Maximum water-level changes resulting from these tests are listed in table 12.

The distribution of water-level changes greater than 1 ft are shown (fig. 36) for the spreading of 0.6 Mgal/d over 32 acres for 1 year.

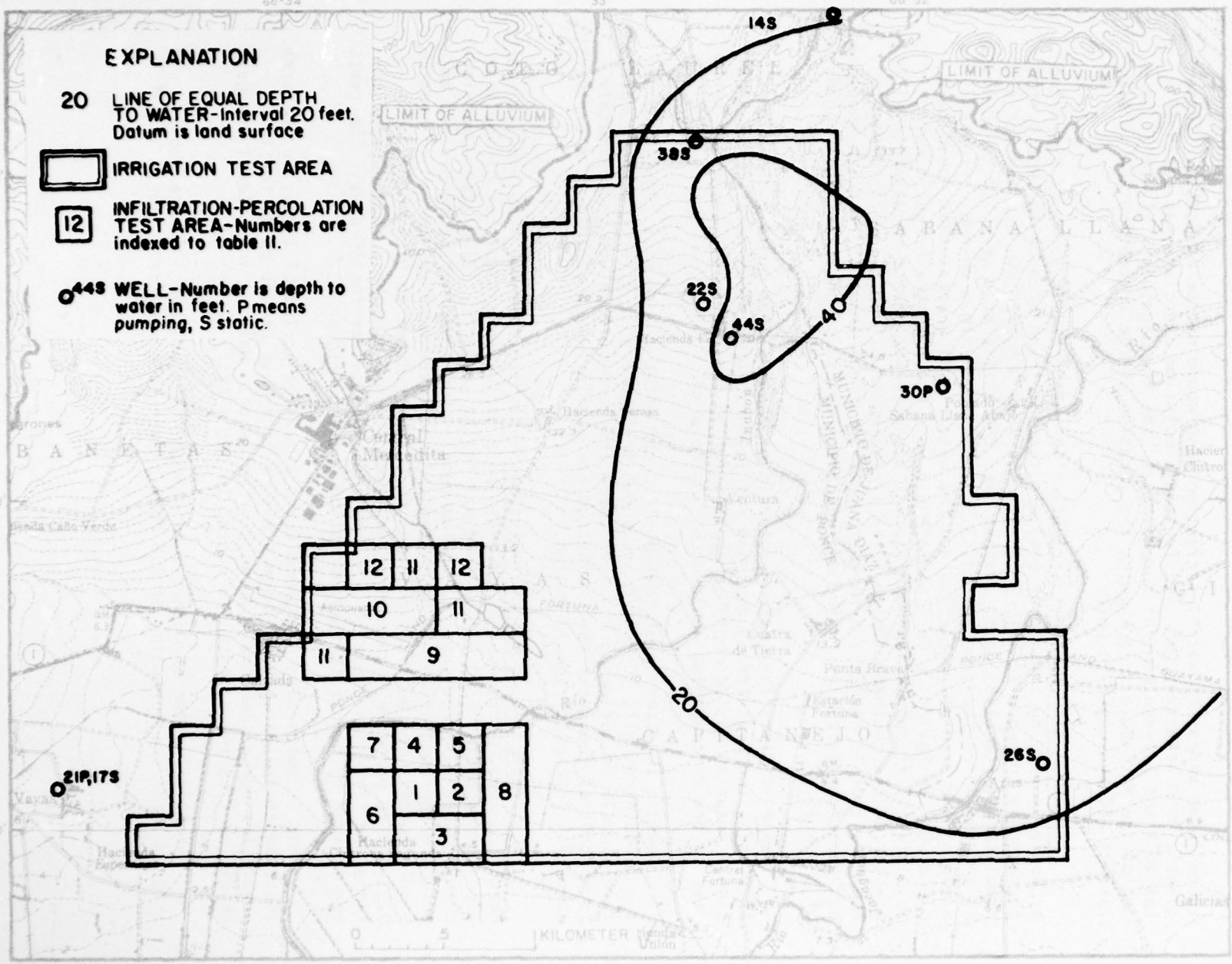


Figure 33.--Depth to water and location of irrigation and infiltration-percolation simulation sites in the Mercedita area.

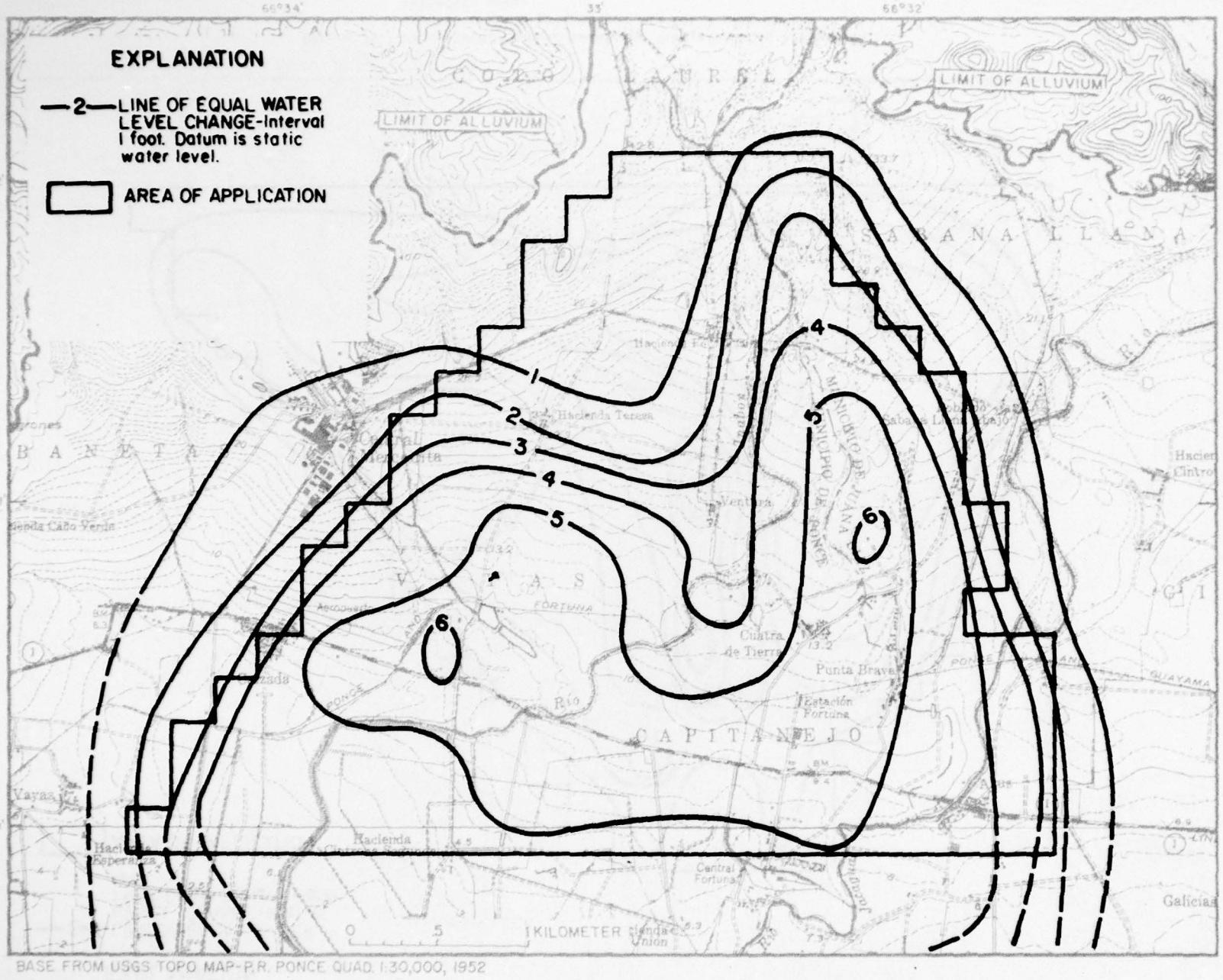


Figure 34.--Water-level changes resulting from simulated irrigation with 20 million gallons per day for 35 days in the Mercedita area.

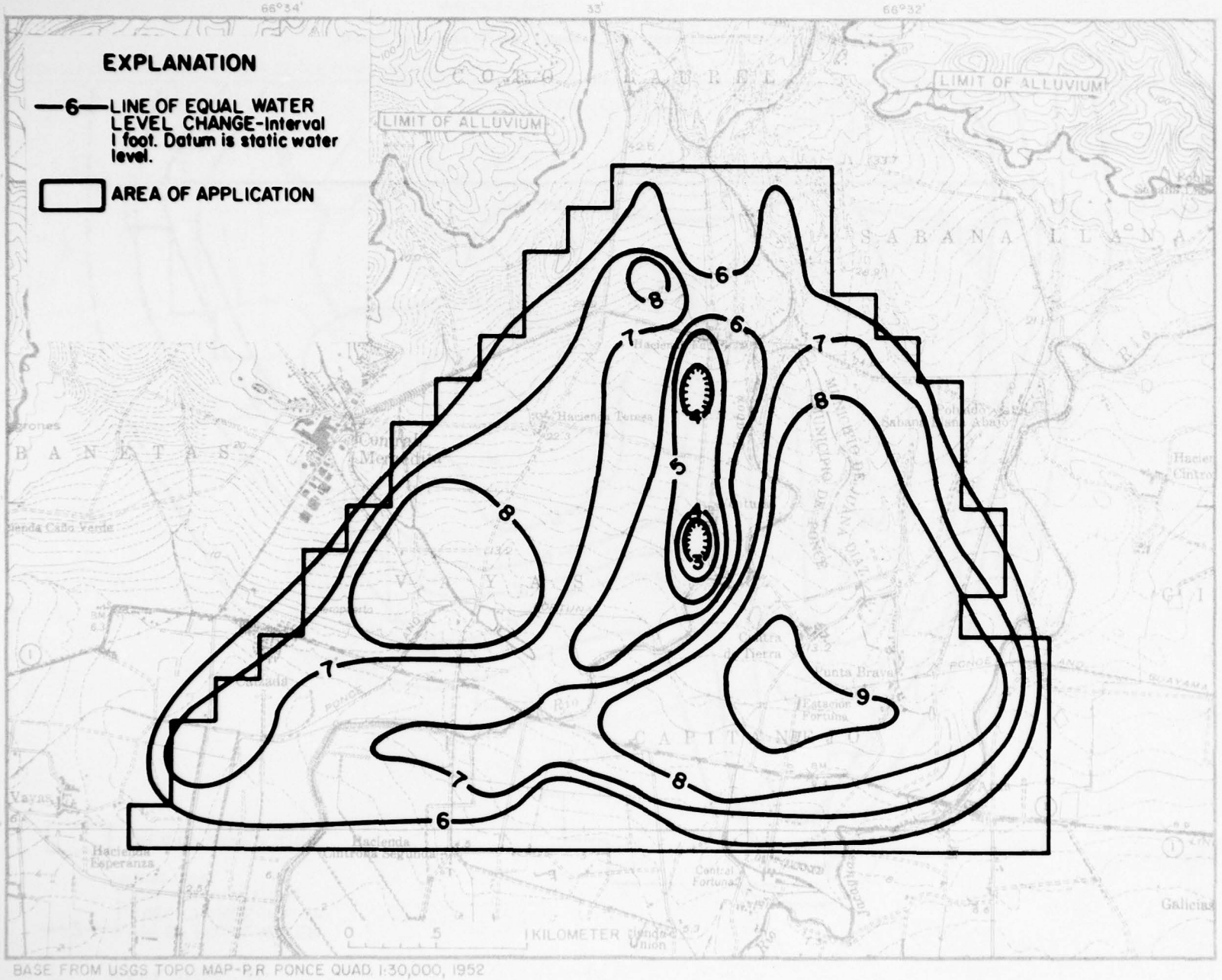


Figure 35.--Water-level changes resulting from simulated irrigation with 20 million gallons per day for 1 year in the Mercedita area.

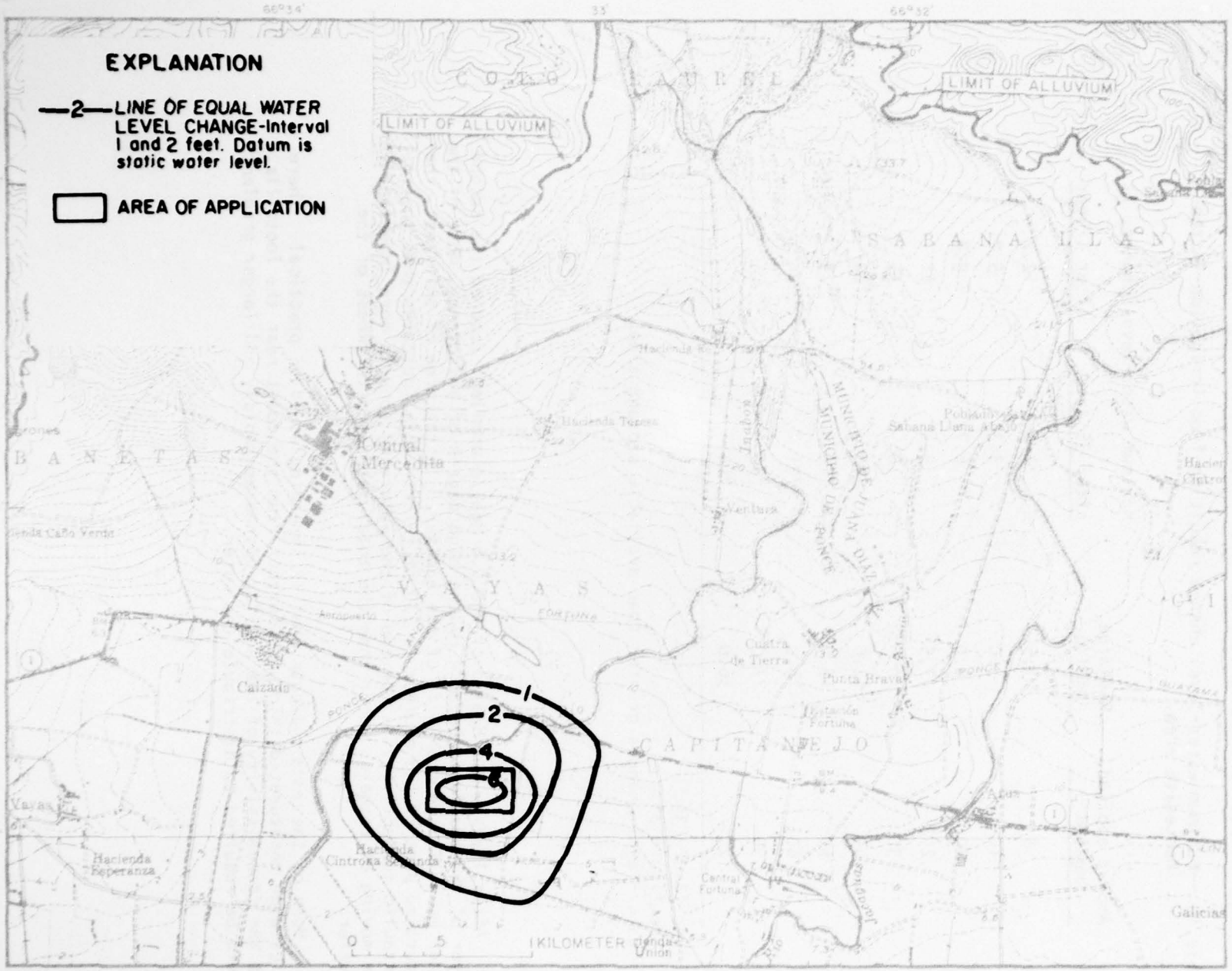


Figure 36.--Water-level changes resulting from infiltration-percolation simulation with 0.6 million gallons per day over 32 acres for 1 year in the Mercedita area.

Table 10.--Maximum water-level change resulting from irrigation in the Mercedita area.

Amount applied, Mgal/d	Recharge, Mgal/d	Maximum water-level change, ft after 35 days	Maximum water-level change, ft after 1 year
5	1.5	1.8	2.2
10	3.0	3.3	5.2
20	6.0	[1] 6.7	[2] 9.8
25	7.5	9.4	11
30	9.0	10	15
40	12.0	15	[3]20
50	15.0	[3]16	[3]24
60	18.0	[3]21	
90	27.0	[3]33	
120	36.0	[3]44	

[1]See figure 34.
[2]See figure 35.
[3]Water-level changes greater than available storage area.

After 1 year, 0.2 Mgal/d of the 0.6 Mgal/d applied, reached the second layer of the aquifer. Because of the high degree of anisotropy, most of the water moved in the top 30 ft of the aquifer. In the area of this test, the saturated part of the aquifer is 270 ft thick. This indicates that the hydraulic conductivity in the top of the saturated zone is more important in the moving of recharge water than the total saturated thickness of the aquifer.

None of the tests indicate that IP spreading would be practical. There is greater unsaturated thickness farther from the coast near the foothills, but the transmissivity of the aquifer decreases rapidly and larger gradients would be required to distribute the water.

Table 11.--Maximum water-level change resulting from high-rate infiltration in the Mercedita area after 35 days.

Area, acre	Maximum water-level change, ft	Mgal/d	Rate, Mgal/d per acre	Recharge, ft/d	Location[1], see figure 33
16	11	0.6	0.04	0.11	1
32	12	1.3	.04	.11	1, 2
80	[2]43	3.2	.04	.11	[1]1-4
96	3.9	3.8	.04	.11	[1]1-5
128	[2]49	5.1	.04	.11	[1]1-6
144	[2]50	5.8	.04	.11	[1]1-7
192	[2]59	7.7	.04	.11	[1]1-8
256	[2]67	10	.04	.11	[1]1-9
368	[2]73	15	.04	.11	[1]1-11
32	6.1	.6	.02	.06	1, 2
80	[2]17	1.6	.02	.06	1, 4
144	[2]26	2.9	.02	.06	[1]1-7
192	[2]31	3.8	.02	.06	[1]1-8
256	[2]31	5.1	.02	.06	[1]1-9
304	[2]36	6.1	.02	.06	[1]1-10
400	[2]37	8.0	.02	.06	[1]1-12
64	4.4	.6	.01	.03	[1]1-3
144	9.3	1.4	.01	.03	[1]1-7
304	12	3.0	.01	.03	[1]1-10

[1] Where multiple locations are indicated, the numbered areas are inclusive.

[2] Waterlogging likely outside of application area.

Table 12.--Maximum water-level change resulting from high-rate infiltration in the Mercedita area for 1 year.

Area, acre	Maximum water-level change, ft	Amount applied, Mgal/d	Recharge, Mgal/d	Rate Mgal/d per acre	Location, see figure 33
16	13	0.6	0.2	0.04	1
32	16	1.3	.4	.04	1, 2
32	6.7	.6	.2	.02	1, 2
80	16	1.6	.5	.02	[1]1-4

[1] Includes all sites within the range.

Jobos Area

The test area in the vicinity of Jobos is situated on one of the narrower parts of the south coast alluvial plain. The area is almost entirely rural and almost entirely given over to the production of sugarcane. The plain slopes gently from the foothills to Bahía de Jobos (Jobos Bay) and is traversed by two stream channels, which carry the Ríos Seco and Melanía. Both streams are, as the name of one suggests, dry most of the time.

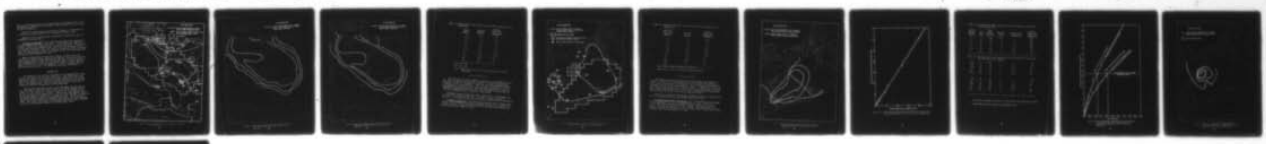
The water table is fairly close to the ground in the western part of the test area and in sections close to Jobos Bay. However, in areas close to the bedrock hills the water table is 30 to 50 ft below ground level.

The saturated thickness of the alluvium in the area does not exceed 100 ft. This is considerably less than at Mercedita, Yauco, Guayanilla and Tallaboa, but about comparable with the valley of the Ríos Pastillo and Cañas. A small zone near the east end of the test area has a hydraulic conductivity of about 100 ft/d but the remainder of the area has low hydraulic conductivity. The entire area is considered to be between alluvial fans and as such exhibits lower hydraulic conductivity than in the center of the fans. This fact combined with the limited thickness of the alluvium indicates that larger gradients are needed to move the water in the aquifer and recharge conditions are less than ideal.

There is some compensation that can be considered for this area, however. Though limited in the north-south dimension by the rock hills and the bay, the east and west dimensions are not limited, at least in the context of this consideration. This means the area of recharge can be increased to compensate for the stated limiting factors. Another consideration is that in other

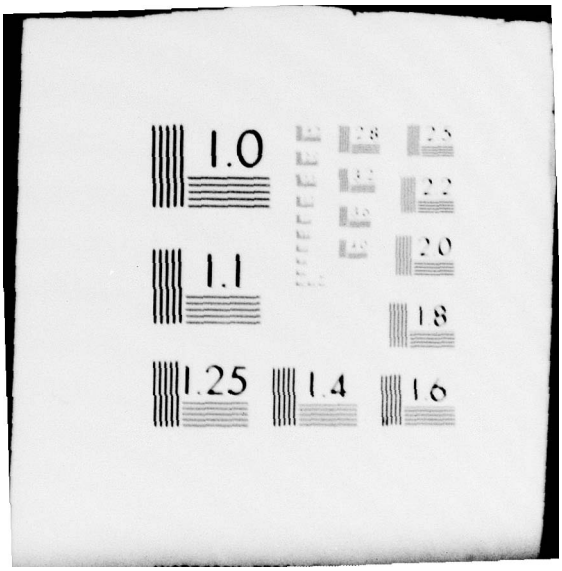
AD-A074 703 GEOLOGICAL SURVEY FORT BUCHANAN PR WATER RESOURCES DIV F/G 8/8
WATER BUDGET AND HYDRAULIC ASPECTS OF ARTIFICIAL RECHARGE, SOUT--ETC(U)
MAY 79 J E HEISEL, J R GONZALEZ
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tests it was found that most of the water moved in the upper 30 ft of the saturated zone; therefore, the thickness of the alluvium is not as critical as might be expected.

The area is located about 5 miles west of Guayama. If waste water is to be used it would be supplied from the Guayama treatment plant.

Because of the limiting factors stated above IP simulations were not attempted in the Jobos area.

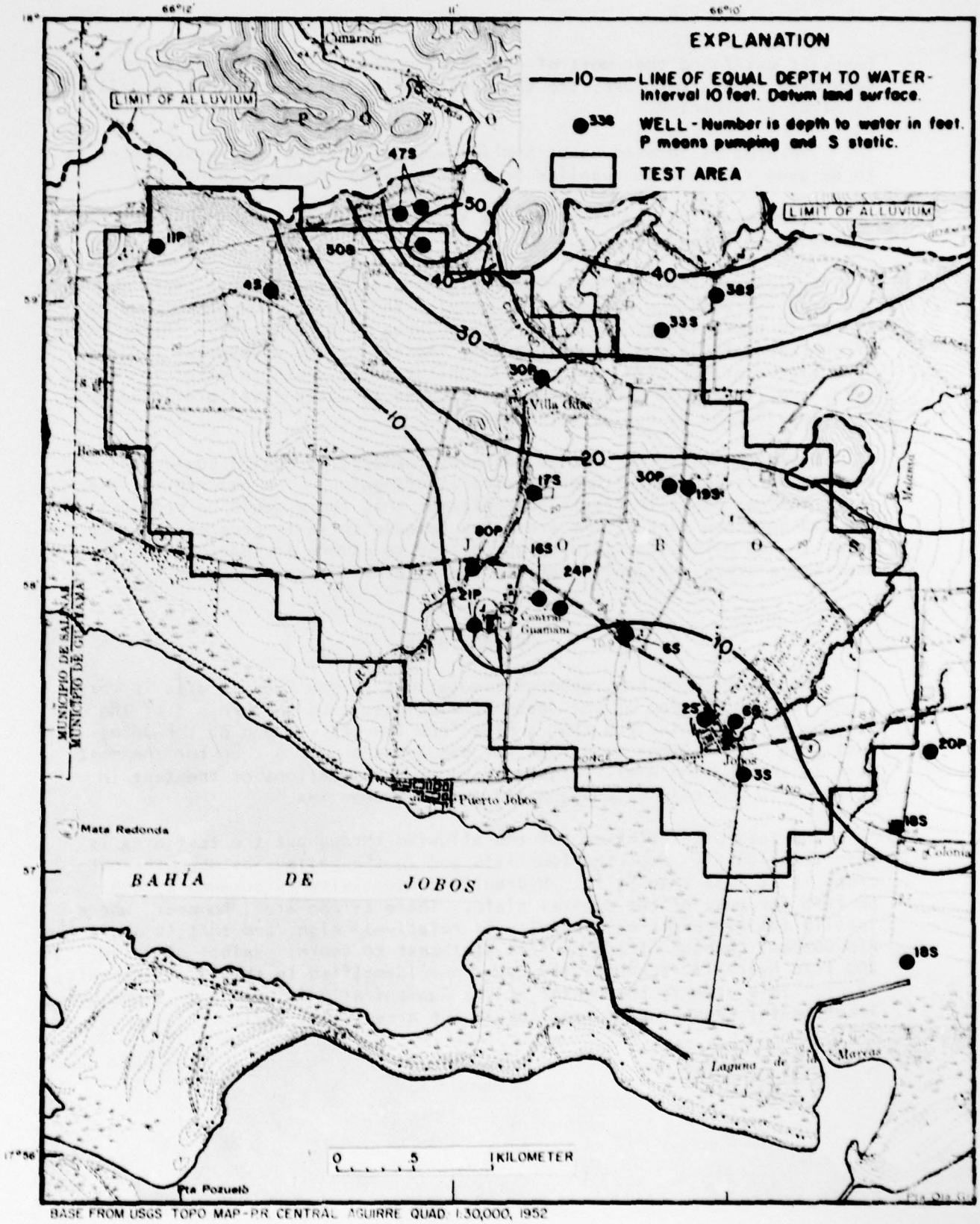
Irrigation simulations.--Ten irrigation experiments were performed in the area representing Jobos on the model. The application of amounts as listed in table 13 was simulated over an area of 3,000 acres. The mounding of the water table was gradual so that the effect was widespread and not very high over the area. Figure 37 indicates the depth to water in February 1975, and figures 38 and 39 show the changes in water level predicted when applying 18, and 36 Mgal/d for 1 year.

Based on the pattern of water-level changes, 18 Mgal/d could be applied as irrigation without causing waterlogging. The pattern of water-level changes shown in figure 38 indicates that there would be problems in the southeastern part of the area, but because there is greater depth to water in the north, it would be acceptable to remove irrigation from the near-shore areas and apply that removed to areas near the foothills.

Guayama Area

The location of the recharge simulations in the Guayama area is very close to the location of the Jobos simulations. The western end of the Guayama test area is less than a mile from the eastern end of the Jobos test area. Conditions described for the Jobos area are true for the most part in the Guayama area. Figure 40 shows the locations of the test in relation to the city of Guayama and the Caribbean Sea.

The saturated thickness of the alluvium throughout the test area is less than 100 ft. Near the foothills and in the valleys between the outcrops it is less than 50 ft. Hydraulic conductivity is between 25 and 50 ft/d for most of the coastal plain. There is one area, however, where locally the hydraulic conductivity is relatively high, and that is where the Río Guamaní changes direction from southwest to south. Values of up to 200 ft/d hydraulic conductivity have been identified in this area (Bennett, 1976). This area is the center of the Guamaní alluvial fan and is the best location for ground-water supplies in the area (Díaz, 1971).



BASE FROM USGS TOPO MAP-PR CENTRAL AGUIRRE QUAD 1:30,000, 1952

Figure 37.--Depth to water and location of irrigation simulations in the Jobos area.

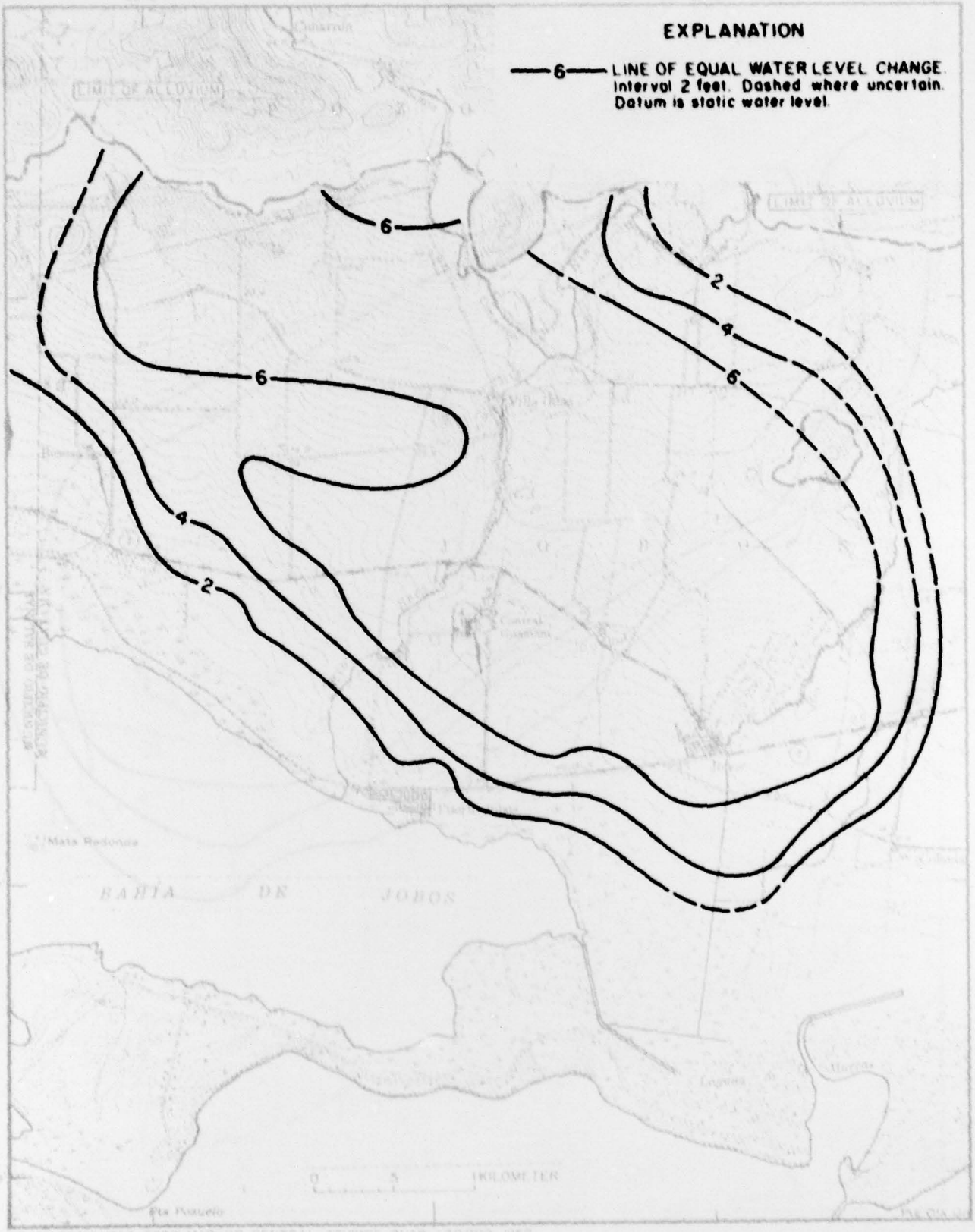


Figure 38.--Water-level changes resulting from simulated irrigation with 18 million gallons per day for 1 year in the Jobos area.

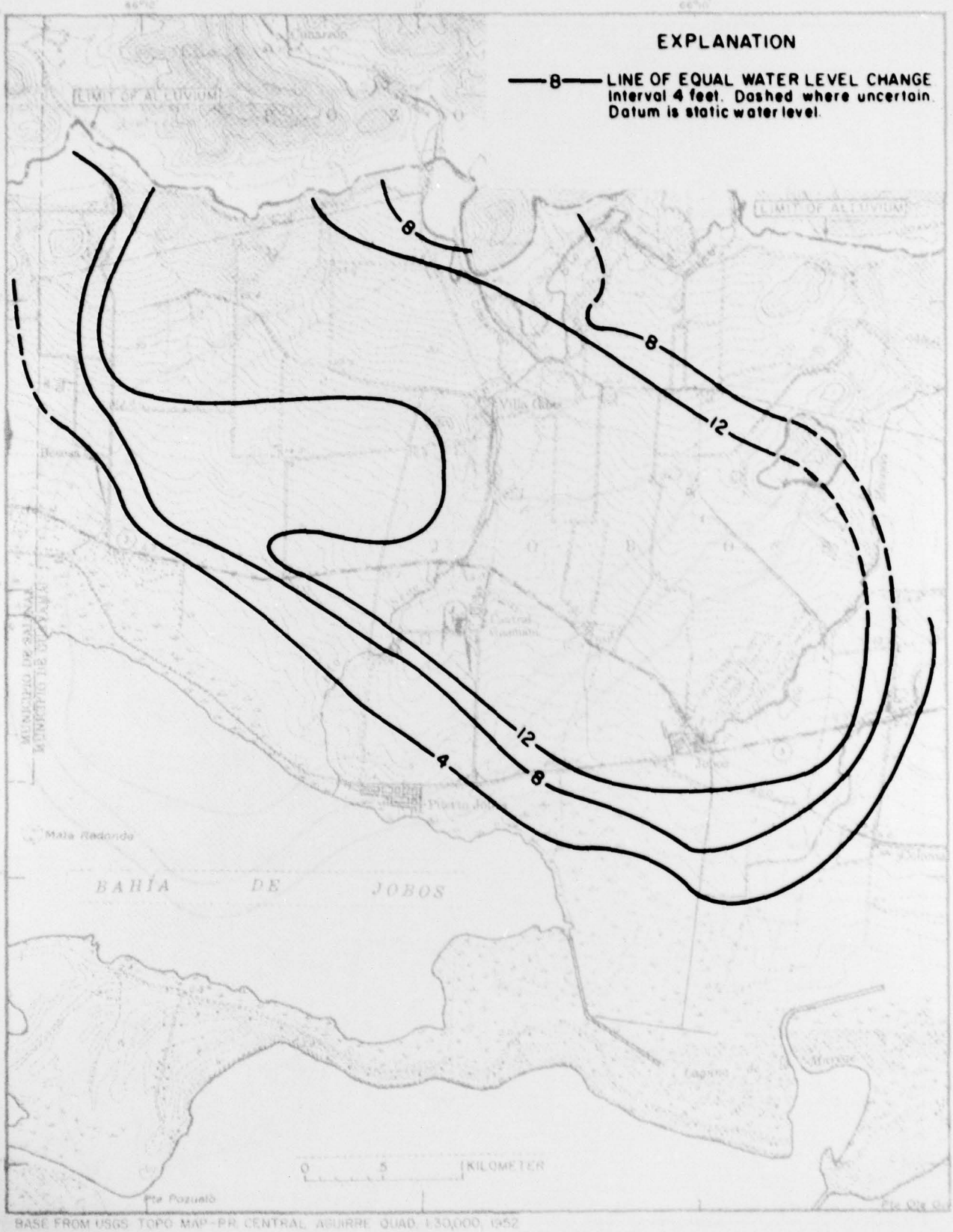


Figure 39.--Water-level changes resulting from simulated irrigation with 36 million gallons per day for 1 year in the Jobos area.

Table 13.--Maximum water-level change resulting from irrigation in the Jobos area.

Rate, Mgal/d	Recharge, Mgal/d	Maximum water-level change, ft
1.8	0.5	0.8
3.0	.9	1.5
4.2	1.3	1.5
5.4	1.6	1.5
7.2	2.2	2.2
9.0	2.7	3.0
12	3.6	4.5
18	5.4	[1] 6.0
36	10.8	[2] 12
60	18	22

[1] See figure 38.

[2] See figure 39.

Note: Waterlogging would occur for applications of 36 and 60 Mgal/d.

The plain east of the Río Guamaní, referred to as the Guayama alluvial fan, does not possess the qualities necessary to provide good recharge. Prospects are best for recharge in the valley of the Río Guamaní northwest of Guayama and in the Guamaní fan. There has been industrial activity on the Guamaní fan starting in 1966. When the industries moved in, land was removed from sugarcane production and irrigation eased in these areas cutting off a valuable source of recharge to the aquifer.

The depth to water varies from zero at the shore of the Caribbean Sea to almost 30 ft along the foothills. The depth to water is shown in figure 40. Also shown are the locations of the irrigation and IP simulations.

Irrigation simulations.--The total area covered by the irrigation simulations in the vicinity of Guayama corresponds to 2,100 acres. Table 14 is a listing of the 10 irrigation experiments giving the amount applied and the maximum water-level change for each.

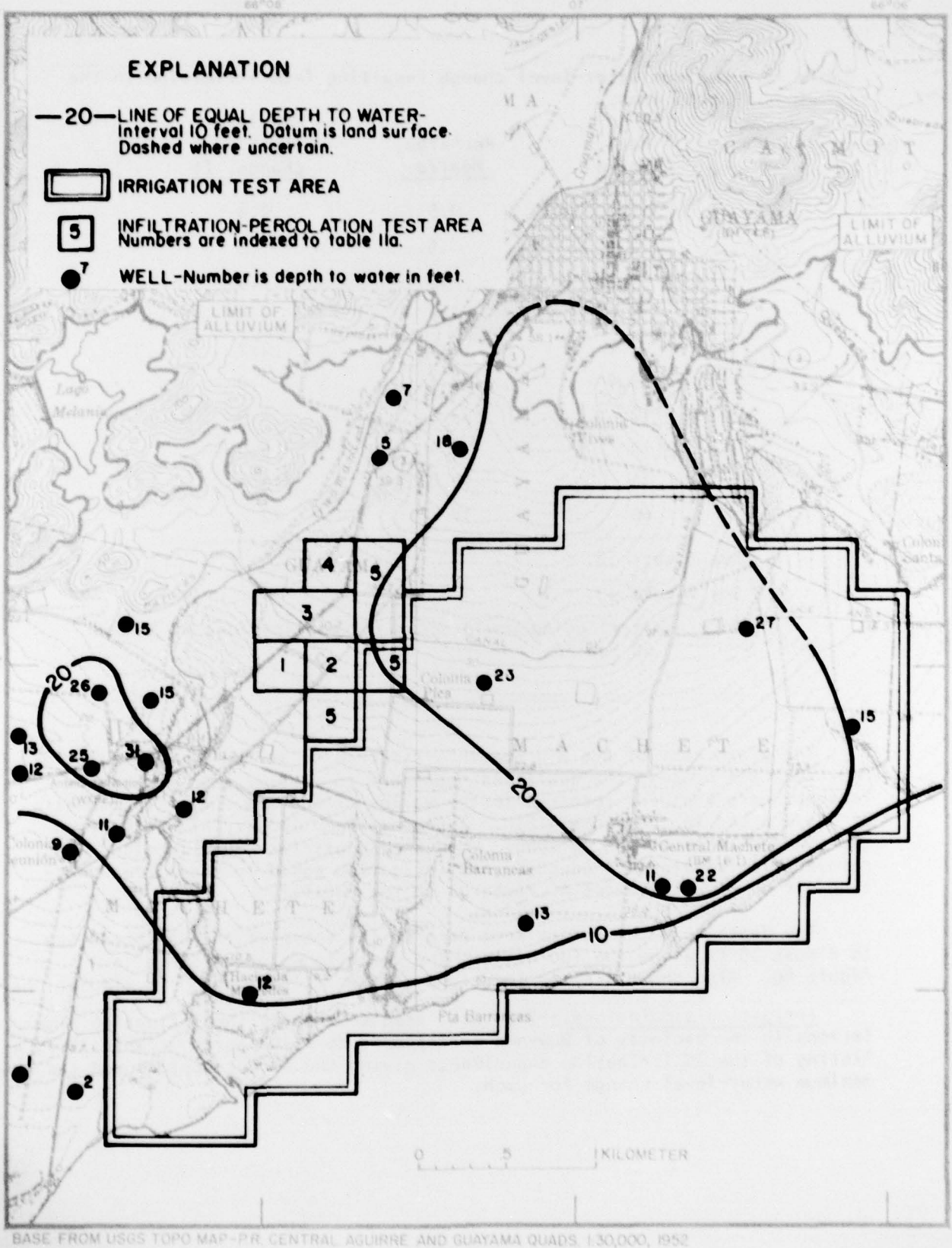


Figure 40.--Depth to water and location of irrigation and infiltration-percolation simulation sites in the Guayama area.

Table 14.--Maximum water-level change resulting from irrigation in the Guayama area.

Amount of water added, Mgal/d	Recharge, Mgal/d	Maximum water-level change, ft
1.8	0.5	0.75
3.0	.9	1.5
4.2	1.3	3.0
5.4	1.6	3.0
7.2	2.2	4.5
9.0	2.7	6.0
12	3.6	9.0
18	5.4	[1]11
[2]36	10.8	25
[2]60	18	40

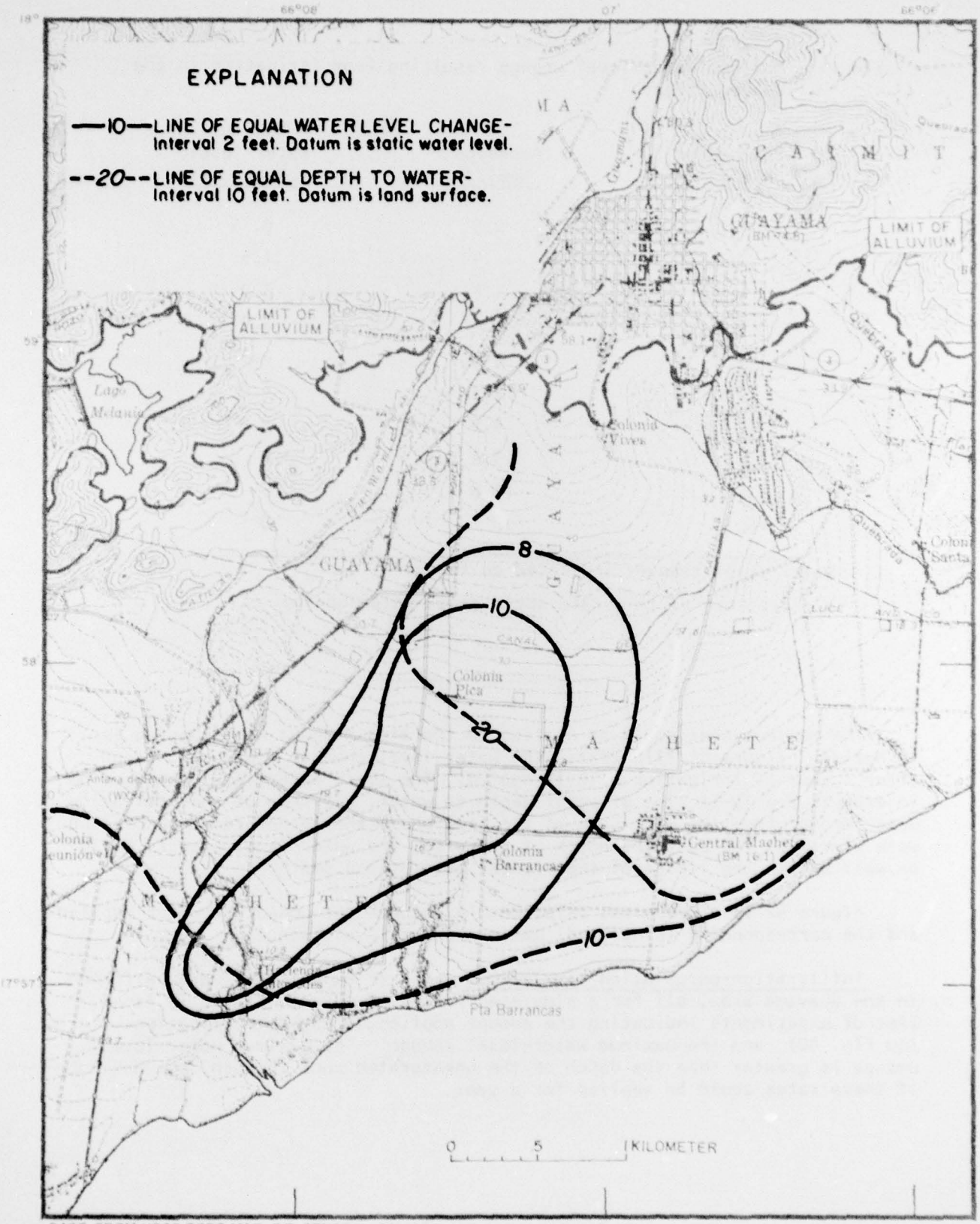
[1] Water-level changes indicated on figure 41.

[2] Applications at this rate would cause waterlogging.

The maximum that could be applied to the area without waterlogging is 18 Mgal/d. Figure 41 illustrates the water-level changes that would occur after 1 year of irrigation with 18 Mgal/d. The 10-ft water-level change line intercepts the 10-ft line of equal depth to water. If some of the irrigation were removed from the west part of the area where the interference occurs and were placed to the east and north of the area, the water-level changes would be well within the limits of the present unsaturated depth.

Figure 42 is a graphical relationship between the amount of water applied and the corresponding (simulated) maximum water-level change.

Infiltration-percolation simulations.--Six IP experiments were performed in the Guayama area, all for a simulated period of 1 year. Table 15 is a list of experiments indicating the amount applied, area, rate, location (on fig. 40), and the maximum water-level change. The maximum water-level change is greater than the depth of the unsaturated zone in each case and none of these rates could be applied for a year.



BASE FROM USGS TOPO MAP-P.R. CENTRAL AGUIRRE AND GUAYAMA QUADS. 1:30,000, 1952

Figure 41.--Water-level changes resulting from simulated irrigation with 18 million gallons per day for 1 year in the Guayama area.

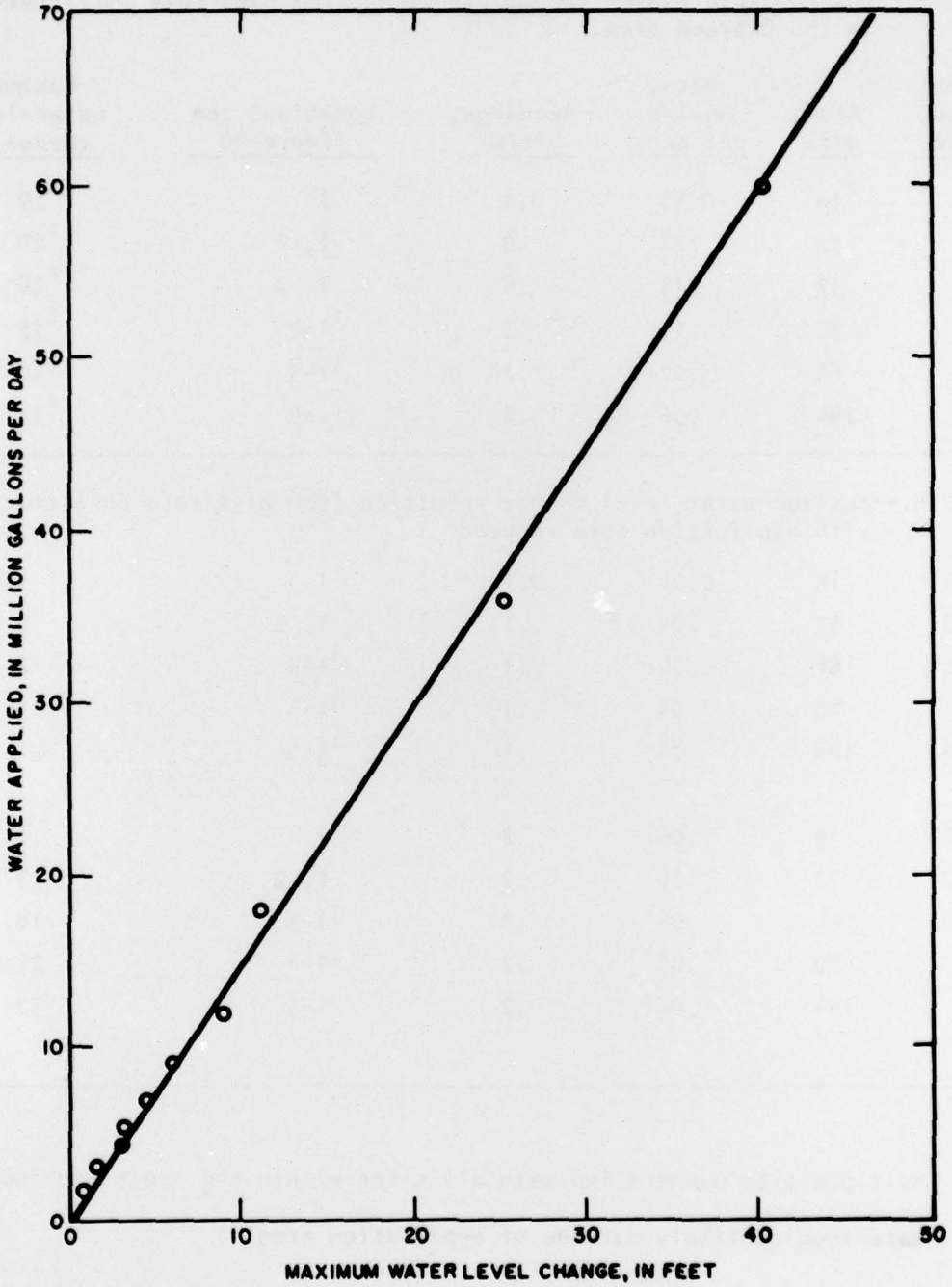


Figure 42.--Relationship between maximum water-level change and simulated irrigation for 1 year in the Guayama area.

Table 15.--Maximum water-level change resulting from high-rate infiltration in the Guayama area.

Amount applied, Mgal/d	Area, acre	Rate, Mgal/d per acre	Recharge, ft/d	Location[1], see figure 40	Maximum water-level change, ft
4.2	16	0.26	0.8	1	[2]30
9	32	.28	.9	1, 2	[2]60
4.2	32	.13	.4	1, 2	[2]28
9	80	.11	.3	[1]1-4	[2]39
4.2	64	.07	.2	[1]1-3	20
9	144	.06	.2	[1]1-5	[2]33

Table 16.--Maximum water-level change resulting from high-rate infiltration with application rate reduced.

0.64	16	0.04	0.1	1	4.6
1.28	32	.04	.1	1, 2	8.5
2.56	64	.04	.1	[1]1-3	12
3.2	80	.04	.1	[1]1-4	14
5.76	144	.04	.1	[1]1-5	21
.96	16	.06	.2	1	6.9
1.92	32	.06	.2	1, 2	13
3.84	64	.06	.2	[1]1-3	18
4.8	80	.06	.2	[1]1-4	21
8.6	144	.06	.2	[1]1-5	[2]32

[1] Multiple site numbers indicate all sites within the range are included.

[2] Waterlogging likely outside of application area.

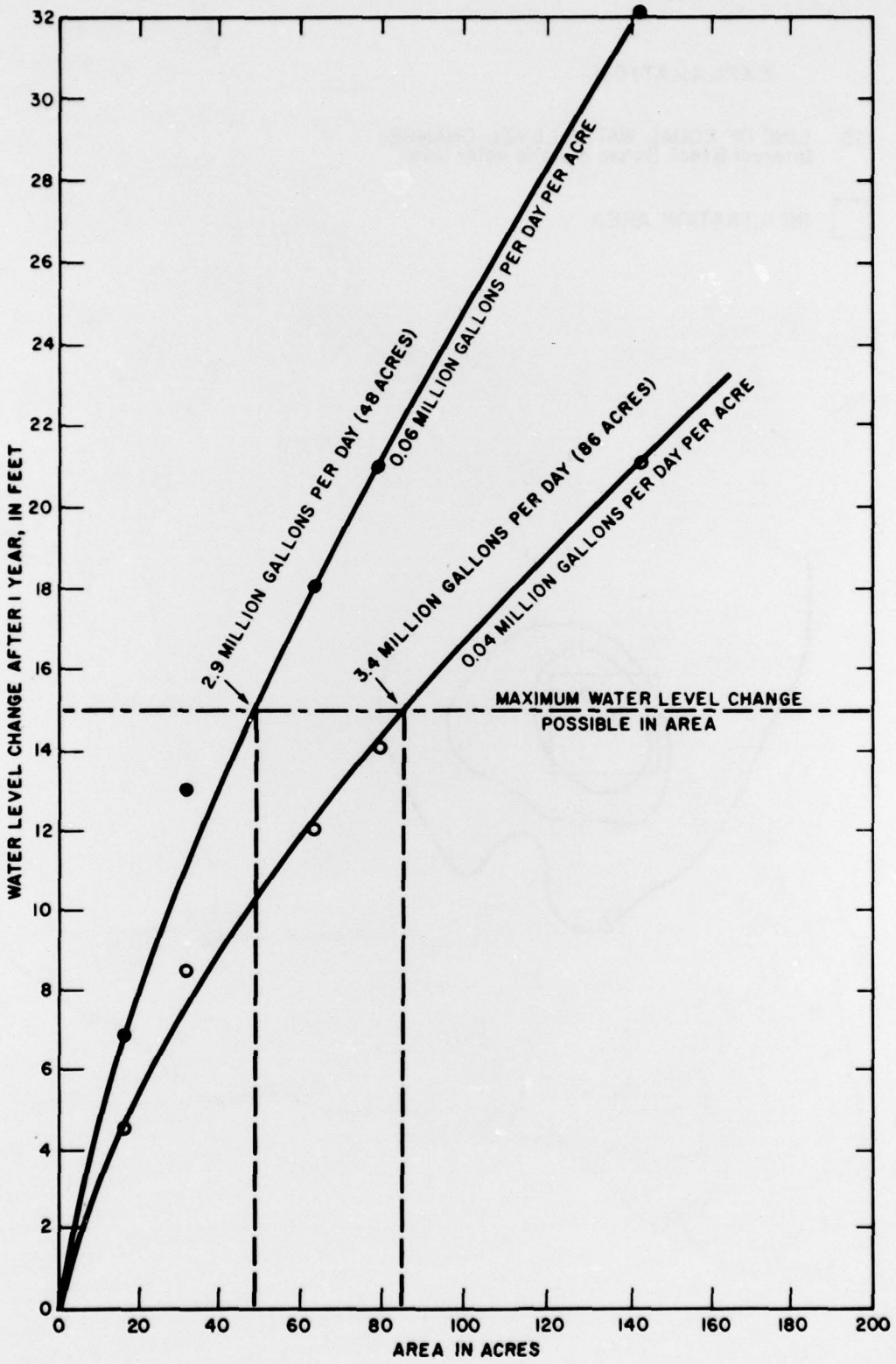


Figure 43.--Relationship between maximum water-level change and area with infiltration-percolation simulated rates of 0.04 and 0.06 million gallons per day for 1 year in the Guayama area.

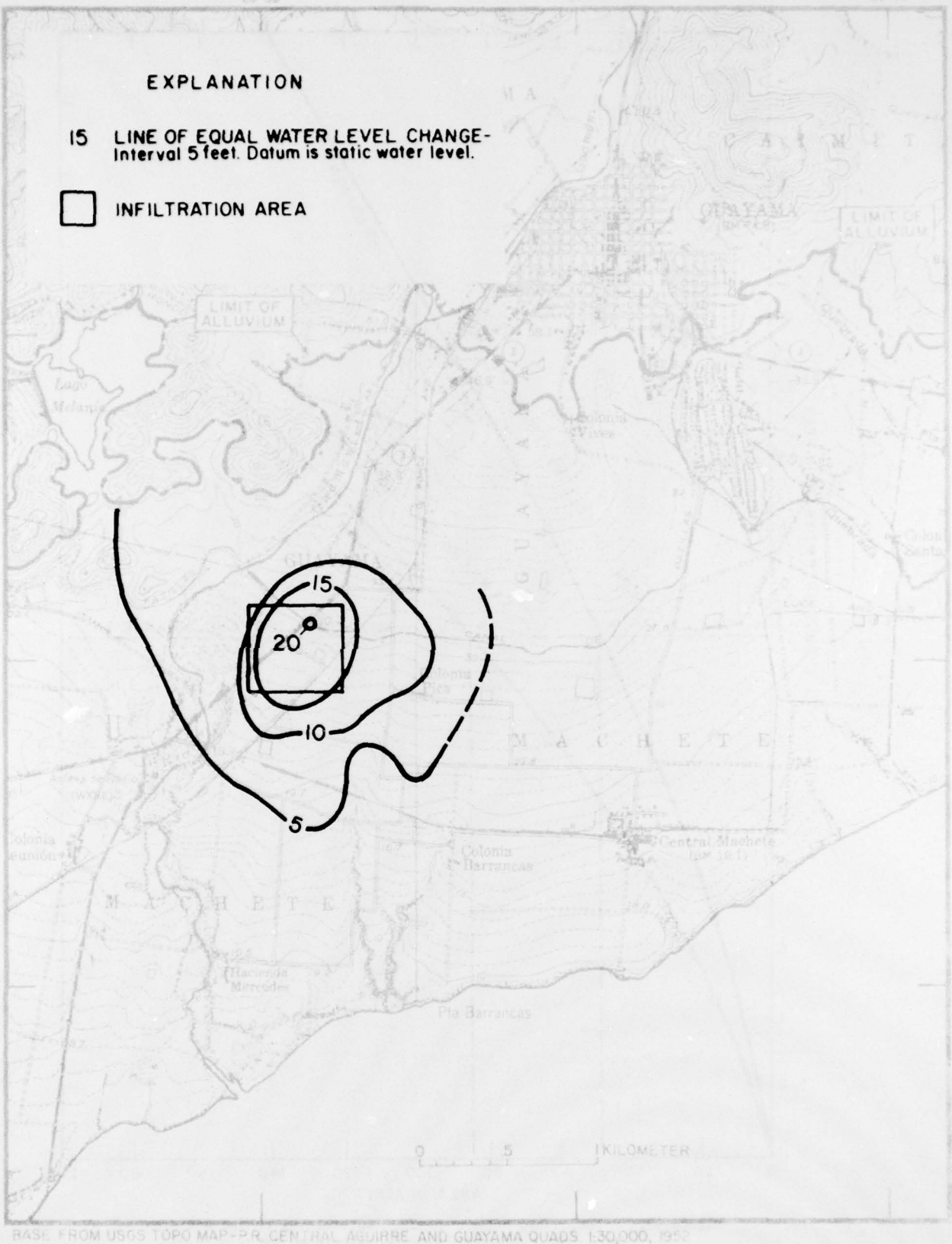


Figure 44.--Water-level changes resulting from infiltration-percolation simulation of 4.2 million gallons per day over 64 acres for 1 year in the Guayama area.

The amounts applied were reduced, and using the same areas, analyses were made for constant rates of 0.04 and 0.06 Mgal/d per acre. These values are listed in table 16. The data of table 16 are plotted on figure 43. At the rate of 0.06 Mgal/d per acre the largest area that could be acommodated without saturation to the ground surface is about 50 acres. The amount that would be involved at this rate and area would be 3 Mgal/d (50 x 0.06). In the same way, the maximum that could be spread at 0.04 Mgal/d per acre is 3 Mgal/d, which would cover about 85 acres.

Figure 44 illustrates the pattern of water-level changes that would occur after 1 year of application of 4.2 Mgal/d to 64 acres. Under this stress the ground would become completely saturated in a small area.

CONCLUSIONS

The limiting factors in all of the simulations are the amount of unsaturated material in the alluvium, the maximum hydraulic gradient permitted by the local topography and depth to water, the hydraulic conductivity, and the amount of water that can be removed by evapotranspiration.

The thickness of unsaturated material is generally about 20 feet. In areas where there is a greater thickness of unsaturated material, the hydraulic conductivity is usually less and the water cannot move through the aquifer as readily.

The water-surface gradient that can be established is related to the depth of unsaturated material, because once this material is saturated in the area of application, a further increase of gradient cannot be attained. The gradient is also affected by the hydraulic conductivity of the aquifer. Where the hydraulic conductivity is high, the required gradient will be less for a given flow; thus more water can be applied per foot of unsaturated material. Where the hydraulic conductivity is low, the reverse is true.

The hydraulic conductivity in the alluvium, in the area of the tests, varies from less than 25 to 200 ft per day with only a limited area greater than 200 ft/day, and the majority of the area 50 ft/day or less.

Where evaporation rates are high, large amounts of the water applied will be lost to this process, and more water must be applied than where the ET rates are low to achieve similar results. For the study area, the ET rate is considered to be uniform. The ET rate affected the results of the irrigation trials more than the IP trials.

When considering an area for artificial recharge certain things must be known about the area. This study has considered only the ability of the aquifer to carry the water and in some aspects presents conservative findings.

The soil zone, what it consists of and how it affects recharge has not been considered.

This study also does not consider the effects of quality of water on artificial recharge. There are two factors that should be considered:

1. Changes of ground-water quality due to difference in quality between the natural ground water and the recharged water, and

2. Changes in aquifer characteristics because of chemical reaction between introduced water and either natural water or the aquifer matrix.

These effects could be serious but it should be possible to evaluate them in advance by a careful analysis of the entire system.

About 10 Mgal/d of waste water could be made available for recharge purposes in the Ponce area in the very near future but larger amounts are included in the experiments to include future recharge possibilities.

Irrigation Trials

Irrigation seems by far the most efficient way to utilize the waste water.

A rule of thumb was used in the irrigation experiments in which 70 percent of the water was considered used up in the ET process. The amount applied was limited by the ET rate and in most places this limit was met before the aquifer was entirely saturated. In actual practice, where the crop use-infiltration ratio is different, the application rate could be changed accordingly.

Some examples of areas necessary to account for all the ET when the ET rate is 0.014 ft/d, and 1 Mgal/d is applied are:

30 percent recharge	153 acres
50	110
70	66

Some of the experiments determined that most of the water will move through the upper layers of the aquifer, and only a small part of the water will move down into the deeper layers. The rate at which the water moves vertically in the aquifer is unknown and although some have attempted to determine this value through rule of thumb techniques no field tests are known in which this value has been determined for the area under study. Tests of the vertical rate of water flow in the areas are necessary before a recharge system can be designed.

Table 17 is a compilation of data from the simulations that gives the amount of water that can be used for irrigation in each area (30 percent going to recharge the aquifer).

Table 17.--Amount of water that can be used for irrigation in the various areas.

Area	Irrigation, Mgal/d	Acres
Yauco	12	570
Guayanilla	9	1,790
Tallaboa	10	740
Mercedita	20	3,000
Jobos	18	3,000
Guayama	18	2,100

High-Rate Infiltration

Results of the IP experiments were not encouraging. Most of the water will have to move through the upper layer of the aquifer under the simulated conditions. Water will move so slowly downward that the top layer of the aquifer will distribute most of the water. In one test where vertical movement of water was measured, 0.2 of 0.6 Mgal/d applied, moved to the lower layers of the aquifer. In the area of the test, the top layer represents 30 ft of aquifer and the other layers represent 270 ft of aquifer, so that 67 percent of the water moved in 10 percent of the aquifer. Gradients build up so rapidly under heavy applications that the areas must be increased to accommodate the large amounts of water. For areas with deep unsaturated zones or large transmissivities IP is an acceptable method of recharge, but on the south coast of Puerto Rico conditions are not favorable for this type of recharge.

Injection

When injecting water into an aquifer, slow vertical movement is advantageous because it allows water to flow in the deep layers under the influence of increased pressures, but does not allow the water to flow easily to the surface. Under these conditions the water table will not rise rapidly and the unsaturated zone will not become saturated rapidly. The injection experiments determined that 12 Mgal/d could be injected into the alluvium west of Ponce without waterlogging at the surface.

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