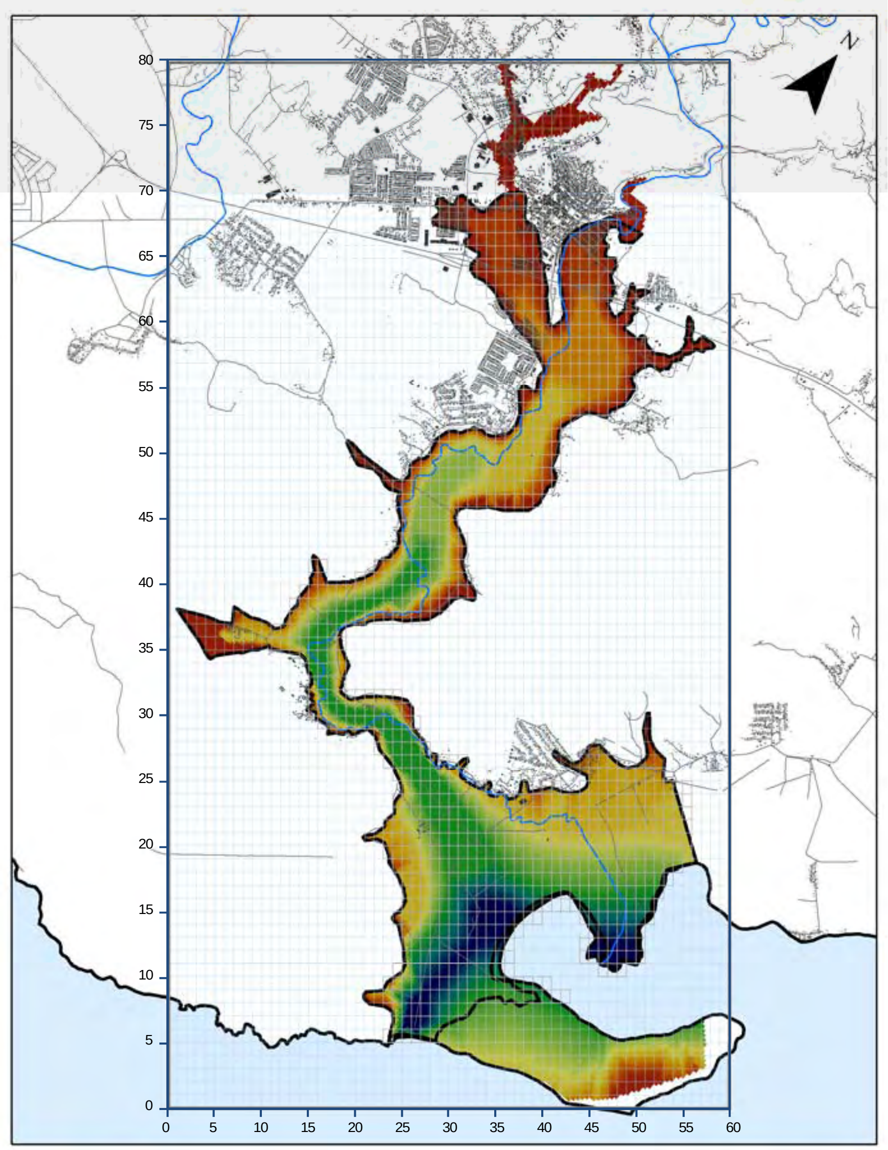
GROUND WATER OPERATIONAL MODEL
YAUCO, PUERTO RICO



June, 2009

PREPARED FOR:

ESTADO LIBRE ASOCIADO DE PUERTO RICO
DRNA
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ABSTRACT

A numerical groundwater model was constructed to simulate groundwater flow in the Yauco Alluvial Valley aquifer. The groundwater flow model was constructed to evaluate future management options, including the potential to increase aquifer firm yield through a conjunctive management of ground and surface water.

The aquifer within the Yauco Valley consists of river alluvium deposited over the incised Juana Díaz formation and Ponce limestone. A finite-difference, numerical model was developed to simulate ground water flow in the Yauco Valley. The single-layer model encompasses the entire alluvial deposits of the valley which extends from the Yauco town to the Caribbean Sea. The model was calibrated to October 1960 and 1970 to 1974 water levels.

Different management scenarios were modeled to analyze and determine how much water can be extracted from the aquifer and evaluate the conjunctive use potential. Results demonstrate that the aquifer could be subjected to a total extraction in the order of 4.6 to 4.8 mgd (1-1.25 mgd above current extractions) without reducing the water levels to a point that could produce saltwater intrusion.

Simulations showed that groundwater extractions could be increased by 5 mgd to 6 mgd during the dry season (March-August) if artificial recharge is provided in the range of 1.3 mgd to 1.95 mgd on a year-around basis. This demonstrates that the potential exists to conjunctively use ground and surface water to increase aquifer yield.

1. INTRODUCTION

Water supplies are limited in the Yauco area, and P.R. Aqueduct and Sewer Authority (PRASA) is proposing to increase water production by enlarging the Yauco filter plant and withdrawing water from Lucchetti dam. Lucchetti dam is the fourth of five interconnected reservoirs comprising the Lajas Valley Irrigation System, which includes the following dams: Guayo, Yahuecas, Prieto, Lucchetti, and Loco. Lucchetti dam impounds Río Yauco upstream of the Town of Yauco. Operation of the five reservoirs in the Southwest Puerto Rico Project, has not been optimized for water yield, and is also loosing capacity to sedimentation. In this region the potential exists to conjunctively use both surface and ground water to increase the available water yield.

Under the concept of conjunctive use, treated wastewater effluent or surplus water from the reservoirs can be used to recharge the aquifer via riverbed recharge or designated recharge areas, thereby using aquifer storage volume to augment reservoir storage.

1.1. Scope and Purpose of Report

The objective of this report is to describe the development of a numerical model of the ground water flow system in the Yauco alluvial valley to simulate its behavior. The model will serve as a tool to analyze different ground water management scenarios, and particularly evaluation of the potential to increase aquifer firm yield through the conjunctive management of ground and surface water. This report describes the hydrology, hydrogeology, ground water flow system boundaries, hydraulic properties, and ground water withdrawals in the study area, and analyzes the potential benefits from recharge to the ground water system in terms of increased yield during periods prone to drought. This report scope does not include the analysis of specific sites or technologies for recharging the aquifer, which is a logical follow-up task once the magnitude of its benefits has been established through modeling.

1.2. Authorization

Preparation of this report has been authorized by the Department of Natural and Environmental Resources (DNER) by contract # 050-08-001302.

2. STUDY AREA DESCRIPTION

The alluvial aquifer within the Yauco Valley is located south (downstream) of the Town of Yauco, Puerto Rico. **Figure 1** presents the location of the study area. The study area extends from the Town of Yauco to the Caribbean Sea with ground surface elevations ranging from 40 m-msl to sea level. The extent of the alluvial aquifer is illustrated in **Figure 2**.

2.1. Land and Water Use

Historically, the Yauco Alluvial Valley has been subjected to flooding and is classified as floodable zone according to the FEMA FIRM (Flood Insurance Rate Map). As a result, the only use of the valley lands has been agriculture. Irrigated sugarcane cultivation was the principal agriculture activity at the Yauco Valley from 1815 to the late 1970s. The principal producers of the region were La Hacienda María (1885-1913), Central Rufina (1901-1968), and Central San Francisco (1913-1977). With industrial development in adjacent valleys, some of the water in Yauco was diverted to heavy industrial use starting in the late 1960s.

During the period of sugarcane cultivation, water extractions were as much as 8 mgd, and between the 1970s and 1984 ground water withdrawals declined from about 8 mgd to about 2 mgd, the result of declining agricultural and industrial operations (Quiñones-Aponte, 1986). The combination of high water withdrawals during the early 1970s and the low rainfalls contributed to saltwater intrusion during this period (Quiñones-Aponte, 1986).

Today's irrigated agriculture consists mostly of bananas and mangoes (**Figure 2**). The estimated groundwater use in 2008 was approximately **3.6 mgd** extracted from 17 wells distributed along the aquifer. The farms in the Yauco Alluvial Valley are shown in **Table 1**.

Table 2 presents the wells currently in operation and their location is shown in **Figure 2**. Not all wells have the required flow meter installed, and withdrawals for wells without meters were estimated as proportional to the irrigated area on similar farms with metered wells.

Table 1: Farms at the Yauco Alluvial Valley.

Farm	Type of Crop	Irrigated Area (acres)	Extraction Wells (number)
Bananera Pagán	Bananas	285	5
Bananera Planel	Bananas	214	2
Modesto Canaval Farm	Bananas	94	2
Hay Farm	Hay	264	3
Fabre Farm	Bananas	113	2
Tropical Fruit	Mangos and Bananas	574	2
Unknown Farm	Bananas	41	1
	Total	**1,584**	**17**

Table 2: Extraction Wells along Yauco Alluvial Aquifer during 2008.

Well ID	Supplied Farm	Location (Geographic coordinate system)		Average Annual Extraction (mgd)
		Longitude	Latitude	
JP 1	Bananera Pagán	66° 50' 21.23'' W	18° 01' 37.04'' N	0.32
JP 2	Bananera Pagán	66° 50' 28.09'' W	18° 01' 34.22'' N	0.31
JP 3	Bananera Pagán	66° 50' 38.79'' W	18° 01' 43.27'' N	0.06
JP 4	Bananera Pagán	66° 50' 21.70'' W	18° 00' 19.62'' N	0.24 △
JP 5	Bananera Pagán	66° 50' 29.80'' W	18° 00' 30.02'' N	0.15 △
BP 1	Bananera Planel	66° 50' 20.91'' W	18° 01' 31.93'' N	0.24 △
BP 2	Bananera Planel	66° 50' 10.75'' W	18° 00' 53.80'' N	0.49 △
CF 1	Modesto Canaval Farm	66° 50' 20.64'' W	18° 01' 25.07'' N	0.14 △
CF 2	Modesto Canaval Farm	66° 50' 14.90'' W	18° 01' 7.912'' N	0.14 △
HF 1	Hay Farm	66° 50' 39.25'' W	17° 59' 25.74'' N	0.14 △
HF 2	Hay Farm	66° 50' 32.23'' W	17° 59' 37.97'' N	0.14 △
HF 3	Hay Farm	66° 48' 43.24'' W	17° 59' 58.60'' N	0.14 △
FF 1	Fabre Farm	66° 50' 14.06'' W	17° 59' 19.60'' N	0.18 △
FF 3	Fabre Farm	66° 50' 23.88'' W	17° 59' 47.21'' N	0.16 △
TF 1	Tropical Fruit	66° 49' 7.32'' W	17° 59' 17.07'' N	0.38
TF 2	Tropical Fruit	66° 49' 46.01'' W	17° 59' 9.97'' N	0.24
UF 1	Unknown Farm	66° 50' 13.32'' W	18° 00' 4.03'' N	0.12 △
				Total 3.59

△ Estimated based on water per acre determined from the available data.

2.2. Previous Investigations

Ground water conditions along the Yauco area have been subject to several prior studies by the USGS, but the most recent in-depth analysis carries a publication date of 1986. The studies reported by the USGS for this area are listed below:

- Geology and Hydrogeology of the Caribbean Islands Aquifer System of the Commonwealth of Puerto Rico and U.S. Virgin Islands (Renken and others, 2000).

- Simulation of the Ground water Flow in the Río Yauco Alluvial Valley, Yauco, Puerto Rico (Quiñones-Aponte, 1986).
- Water Resources of the Guayanilla-Yauco Area, Puerto Rico (Crooks and others, 1968).
- Coastal Salinity Reconnaissance and Monitoring Coast of Puerto Rico (Díaz, 1974).
- Water Budget and Hydraulic Aspects of Artificial Recharge, South Coast of Puerto Rico (Heisel and González, 1979).
- Electrical Analog Simulation of the Aquifers along the South Coast of Puerto Rico (Bennett, 1976).

3. HYDROGEOLOGIC FRAMEWORK

3.1. Rainfall and Evapotranspiration

Mean annual rainfall is about 46 inches at the northern border of the study area, decreasing to about 30 inches at the coast, and the total mean annual rainfall in the study area is about 35 inches. There are three rain gage stations in the study area with record periods dating from 1955, as presented in **Table 3**.

Table 3: Rain Gages in the Study Area.

Rain Gage	Record Period	Years of Data	Mean Annual Rainfall (in/yr)
Yauco 1 S	1955-1969	14	30
Boca	1996-2008	12	37
Central San Francisco	1955-1995	50	31

The location of the rain gage stations is presented in **Figure 3**. The Central San Francisco and Boca station are close to each other and the rainfall data from both stations were combined to form a single record. **Figure 4** presents the mean monthly rainfall variation for each rain gage. **Figure 5** and **Figure 6** present the rainfall variation over time for the combined data at Central San Francisco and Boca stations and for Yauco 1 S, respectively. There are notable differences in rainfall between seasons with 55% of the rainfall occurring between August and November. The driest periods recorded in this area were in the early 1970s and the mid-1990s where rainfall decreased by about one third (**Figure 5**).

A mean annual evapotranspiration was estimated by Bennett (1976) as 48 inches. Mean annual pan-evaporation rate at the Lajas Experimental Station (the station most similar to the study area) is 66.34 inches, which converts into a mean annual evapotranspiration rate in the study area of 40 inches per year using a pan coefficient of 0.6 (Maidment, 1993).

3.2. Streamflow

The major stream in the study area is Río Yauco with a drainage area of 50 mi^2. Waters from Río Yauco are impounded by Lucchetti Reservoir 12 km upstream of the PR-2 bridge. **Figure 3** shows the location of Río Yauco and its watershed limits including the drainage area impounded by Lucchetti Reservoir. Streamflow data for Río Yauco were obtained from two USGS gage stations, 50126150 and 50128000, with record periods of 33 years (1976-2009) and 24 years (1961-1985) respectively.

3.3. Geology

The aquifer within the Yauco Valley consists of river alluvium deposited over the incised Juana Díaz formation and Ponce limestone. The study area is composed of three hydrogeologic units: alluvium, Ponce Limestone and Juana Diaz Formation. The main aquifer system consists of alluvial deposits containing lenses of unconsolidated sand and gravel. The Juana Diaz formation is not a principal source of ground water because of its low permeability (Crooks and others, 1968). The Ponce limestone in the valleys is highly fractured and their openings are enlarged by solution as water moves through the fractured zone. This formation yields moderate supplies of water in contrast to the uplands, which is characterized as unproductive (Crooks and others, 1968).

Most of the alluvial valley is located between PR-2 and the Caribbean Sea, a valley-length distance of about 5.5 miles. In this area the width of the alluvium varies from about 0.2 to 1.0 miles. The principal geologic features of the Yauco area are illustrated in plan view in **Figure 7**. The elevation of the base of the alluvium is presented in **Figure 8**, and **Figure 9** presents the average percent of gravel and sand in the study area. In the Yauco Valley, one factor limiting ground water use is the intrusion of saline water into the aquifer. Portions of the alluvial aquifer extend to depths of 20 m below sea level, but upstream from a point about 3 miles inland the base of the alluvium is above sea level thereby eliminating the potential for seawater intrusion in that portion of the aquifer.

3.4. Aquifer Properties

Aquifer properties were estimated from previous investigations. The principal parameters that define aquifer behavior are hydraulic conductivity and specific yield. The hydraulic conductivity defines the facility with which water can move through the aquifer. Bennett (1976) estimated the hydraulic conductivity of the aquifer from specific capacity data of wells. Three different regions of hydraulic conductivity were used in the study area with values ranging from 7.05×10^{-4} m/s at the upper part of the study area to 4.58×10^{-5} m/s in the lower part.

Fresh water enters the aquifer via rainfall percolation and by infiltration through the Río Yauco streambed. Río Yauco is the major contributor to groundwater recharge. The river is seasonally intermittent in the upper part of the study area where the river infiltrates into the alluvial deposits. Return flow from irrigation application, an important source of recharge when sugarcane was cultivated under furrow irrigation, is no longer considered significant due to the prevalence of drip irrigation today.

The specific yield defines the capacity of an aquifer to release groundwater from storage in response to a decline in hydraulic head. Guisti (1971) estimated the specific yield of the aquifer as 0.16 for the Coamo fan deposits, Bennett (1976) use this value in his analog model of the south coast and found a satisfactory match between observed and simulated water levels. This value was used in Yauco.

3.5. Groundwater Levels

Historic water levels have been recorded by the USGS monitoring well "Pittsburg Plate Glass #4" (**Figure 10**) since 1972. Annual variations in water levels fluctuate in the order of 1 to 6 m. As can be seen in the figure, ground water levels dropped in the early 1970s and the mid-1990s. During these periods precipitation at the Central San Francisco gage dropped to 21 and 25 inches/yr respectively, approximately one-third reduction in the mean annual precipitation of 35 in/yr.

The USGS monitoring well is located in the upper part of the aquifer (66°50"32.43'W, 18°01"26.71'N). To augment this information during the study a monitoring well was installed in the lower part of the alluvium. The well was installed at the old Central San Francisco site (66°49"14.40'W, 17°58"50.49'N) and measured water levels from October, 2008 to May, 2009. The water levels in this area ranged from 3 to 3.5 m-msl as presented in **Figure 10**. The recorded levels were used to determine the reasonableness of the levels obtained in the simulation model in that area.

3.6. Saltwater-Fresh Water Interface

The saltwater-fresh water interface was approximated using the Ghyben-Herzberg relationship which defines the depth to the interface of salt water by the following equation:

$$z=40*h_f$$

Where:

z= depth to interface

h_f= head of water table

The relationship, which is based on the density difference between sea water and fresh water, establishes that the interface of saltwater-fresh water will be approximately 40 meters below mean sea level for each meter of fresh water above mean sea level. Using this relationship, the depth of the interface in the Yauco Alluvia Aquifer is below the bottom of the alluvial deposits under current conditions.

In the late 1960s a reconnaissance study (Díaz, 1974) was performed by the USGS along the south coast to define the saltwater intrusion in the coastal alluvial aquifers. The saltwater intrusion limits defined in that study are presented in **Figure 11**. The period of the study coincides with high water withdrawals and a historical extremely low rainfall period, representing the most critical condition the aquifer has been subjected to. Under current conditions the saltwater intrusion limits should be closer to the sea than in the late 1960s less inland that the presented by the study.

4. SIMULATION OF GROUNDWATER FLOW

4.1. Mathematical Model

The mathematical model calculates the basic hydraulic equations that govern the flow of groundwater in the saturated zone. It consists of a set of partial differential equations solved over time and in three-dimensional space. The conceptual model and the hydrogeological data together help to define the conceptual boundary conditions. The hydrogeological stresses complete the boundary condition definition, and provide the temporal and spatial data for solution of the hydraulic equation.

The mathematical model used in this study is the finite-difference ground water model (MODFLOW) developed by the USGS. MODFLOW simulates steady and unsteady flow in an irregularly shaped system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can all be simulated. Hydraulic conductivities or transmissivities for any layer may differ spatially and be anisotropic (hydraulic conductivity may vary as a function of flow direction), and the storage coefficient may be spatially variable. The flow region is subdivided into rectangular blocks in which the medium properties are assumed to be uniform. A flow equation is written for each cell and flow-rate and cumulative-volume balances from each type of inflow and outflow are computed for each time step.

4.2. Model Grid

The model grid is horizontally discretized into rectangular cells of 13,500 m^2. Model cells are arranged in a grid with 81 rows and 50 columns (**Figure 12**). The model contains a single layer corresponding to the alluvial deposits with thickness ranging from 1 m to 40 m.

The National Elevation Dataset was used to assign the top elevations of the aquifer layer (**Figure 13**). The contours presented by Renken (2002) for the bottom of the aquifer were used to prepare a surface within GIS to assign the bottom elevation of each cell in the grid (**Figure 14**).

4.3. Groundwater Recharge and Discharge

Recharge rates for the study area were determined from historic data and model calibrations. Three components contribute to groundwater recharge: precipitation, irrigation, and streambed infiltration. A small part of the total rainfall contributes to aquifer recharge through infiltration, the rest is intercepted by vegetation and then evapotranspirated or is discharged to the sea as surface runoff. Previous studies on the south coast estimate the rainfall recharge rate to be on the order of 10%; this value was tested and adjusted to 20% during the model calibration process.

Recharge rate from irrigation varies depending on the type of irrigation technique employed. Currently the irrigation technique used in the study area is drip irrigation. This type of technique maximizes the use of water by reducing the loss due to infiltration which leads to an infiltration rate on the order of 5%.

The principal contribution to groundwater recharge is provided by riverbed seepage, which is controlled by the hydraulic conductivity of the riverbed plus underlying alluvium. Values of hydraulic conductivity were determined in the calibration process.

An estimated annual water balance is shown in **Table 4**.

Table 4: Average Annual Water Balance, Yauco Aquifer, 2008.

Recharge (Inflow)			Discharge (Outflow)		
Source	mgd	% of Total	Source	mgd	% of Total
Precipitation on Aquifer	1.9	34.1	Extraction by Wells	3.6	65.6
River Leakage	3.4	62.5	River Leakage	0.8	14.1
Irrigation	0.2	3.4	Evapotranspiration	1.1	20.3
Constant Head	0.0	0.0	Constant Head	0.0	0.0
Total	**5.5**	**100**	**Total**	**5.5**	**100**

4.4. Model Boundaries

Boundary conditions are constraints imposed on the model grid to represent the interface between the model calculation domain and the surrounding environment. The boundary conditions used in the modeling are contained in three categories: Specified Head, Specified Flow and No-Flow boundary.

Specified Head Boundary

Specified Head boundaries are used to represent rivers, coastlines, lakes, groundwater divides, known pumping water levels in bores and dewatering targets. This type of boundary was used to represent Río Yauco and the coastline.

This type of boundary was implemented using two MODFLOW packages, River Package and General Head Package. The General Head Package was used to simulate the constant head of zero produced by the Caribbean Sea. Tidal fluctuations in sea levels are minor and were not modeled. The River Package simulates the flow between the aquifer and the river, calculating the interchange of flow from the difference in hydraulic head. The General Head Package simulates the flow required between the aquifer and the boundary to maintain the specified head. **Figure 12** presents the Specified Head boundary cells used in the model.

A river hydraulic model was prepared using HEC-RAS software (Corps of Engineers) to determine the stream stages to be used in River Package. The HEC-RAS program uses uniform, steady and one-dimensional flow to estimate stream stages at each model cross section. Streamflow data used in the HEC-RAS model were obtained from USGS gage stations 50126150 and 50124200 at Río Yauco and Río Guayanilla. The Río Yauco station does not cover the part of the period of simulation and data from Río Guayanilla were used to complete the streamflow series. Río Guayanilla data were adjusted to represent Río Yauco conditions using a relationship determined from the daily streamflow data for the concurrent record period (2002-2009) for the two gages (**Figure 15**).

Specified Flow Boundaries

Specified Flow boundaries are used to represent impermeable boundaries, infiltration sources, lateral inflow or outflow and other known sinks or sources. This type of boundary was used to represent withdrawals from wells. The no-flow boundary condition was used to represent the confinement of the alluvial deposits by the surrounding Ponce Limestone and Juana Diaz Formation, following the assumption that the basin-fill alluvial aquifer has a substantially larger hydraulic conductivity. The Specified Flow Boundary was implemented in the MODFLOW Well Package. The Well package simulates water entering or exiting the aquifer from injection or extraction wells.

4.5. Calibration Analysis

The numerical groundwater model was calibrated by minimizing the difference between measured and simulated groundwater levels in steady-state and transient simulations. In the calibration process the independent variables (aquifer parameters) of the model were adjusted, within realistic limits, to produce the best match between simulated and measured water levels. Calibration methods solve a problem inversely by adjusting the unknowns (aquifer parameters) until the solution matches the observed water levels. This process involves refining the hydrogeological framework, hydraulic properties, and boundary conditions of the model to achieve a reasonable degree of correspondence between the simulated and observed water levels. Typically, hydrologic calibration results never exactly match field data due to the incomplete nature of the available data.

Steady State Calibration

A Steady-State Calibration Model assumes that hydrologic stresses on an aquifer will result in ground water levels and ground- and surface-water flows that vary little over time. Measured groundwater levels during October, 1960 (Crooks and others, 1968) were used to match simulated water levels of the Steady-State Calibration Model (**Figure 16**). Crooks and others (1968) estimate the groundwater use as 5 mgd during the period used for calibration, and present the location of the extraction wells in operation for that period (**Figure 16**). An equal rate of groundwater extraction per well was assumed because detailed information is not available.

Selected hydrologic parameters were varied within a range of reasonable values to achieve the best match to measured groundwater levels. Aquifer parameters modified during calibration of the steady-state model include hydraulic conductivity, streambed vertical hydraulic conductivity and recharge. Initial values for hydraulic conductivity were obtained from Bennett, 1976. The recharge rate due to rainfall was varied between 10% to 20% of the 1960 mean rainfall, obtained from Central San Francisco rain gage, and 20% was used as the final value.

The final hydraulic conductivity for the model ranged from 8.8×10^{-4} m/s at the upper part of the study area to 1.75×10^{-5} m/s in the lower part as presented in **Figure 17**.

Figure 18 present a comparison of measured and simulated water levels.

Transient Condition Calibration

The Transient Calibration Model accounts for the effects of time-variant stresses, such as groundwater withdrawal and recharge. The transient groundwater flow model was calibrated to a time period beginning in 1979 and extending through 1984. Four sets of water-level data were available to calibrate the ground water model. Well extractions were obtained from the previous model prepared by the USGS (Quiñones-Aponte, 1986). Locations of monitoring and extraction wells used in the transient model are shown in **Figure 19**.

The initial specific yield value (0.16) used in the simulation resulted in a poor match to the measured water levels. This value was decreased until finding a reasonable match to measured water levels. The final values of specific yield ranged from 0.10 at the upper part of the aquifer to 0.05 at the coast. **Figure 20** presents a comparison of measured and simulated water levels.

4.6. Sensitivity Analysis

A sensitivity analysis was performed to assess the model's response to changes in selected input parameter values. This analysis was performed to identify the most important parameters in determining aquifer behavior. Results of the sensitivity analysis (**Figure 21**) reveal that aquifer behavior is most sensitive to changes in recharge rate and river streambed conductance.

4.7. Present Condition Model

The model calibrated using historical data was modified to represent the current condition of the aquifer, from 1990 to 2008. This period includes the severe drought during the mid-1990s.

Figure 22 presents the simulated water level compared to the observed water level at the USGS Pittsburg Plate Glass #4 monitoring well. The good fit obtained suggests that withdrawals during the last two decades have been relatively constant, which is the assumption used in this model given the absence of historical pumping data.

4.8. Additional Withdrawals

Additional simulations were undertaken to analyze the aquifer behavior under 2 different operational scenarios: continuous and seasonal extractions. Two conditions were analyzed for the seasonal extractions scenario: 4 month (May-August) and 6 month (March-August) extractions. Extraction wells were placed along the valley between PR-2 and a point 4 km above the shoreline, avoiding the coastal area having the greatest potential for saline intrusion. **Figure 23** presents the minimum water levels during the simulation period for additional continuous extractions of 0.75 mgd to 1.5 mgd. The seasonal extraction scenario showed that the aquifer could be subjected to additional extractions of 2 and 2.75 mgd for the 4 month and 6 month scenarios respectively as presented in **Figure 24** and **Figure 25.** Minimum water levels occurred during the year 1996 (**Figure 22**). Results showed that the aquifer could be subjected to additional extractions on the order of 1.25 mgd, with current recharge conditions. For this extraction the water levels in the aquifer are maintained above one (1) meter over mean sea level in the coastal area, which ensure that the depth of the salt water-fresh water will be below the bottom of the alluvial deposits and reducing the potential of saltwater intrusion.

4.9. Seasonal Extraction and Conjunctive Use Analysis

The Conjunctive Use Model was prepared to analyze different operating schemes to increase aquifer yield by simulating a seasonal increase in the rate of ground water withdrawals during the driest months of the year (March-August). Conceptually, water stored within the aquifer would be drawn upon seasonally to augment surface water resources during periods when reservoirs typically reach their lowest water levels during drought events. Different withdrawal scenarios were simulated for seasonal extraction:

Table 5: Seasonal Extraction for each Simulated Scenarios.

Seasonal Extraction Rate (mgd)	Seasonal Extraction Period (mgd)	Constant Recharge Rate (mgd)
2	March-August	0
2.75	May-August	0
5	March-August	1.95
6	May-August	1.3

Under the four month seasonal withdrawal scenario, about 50% more water can be withdrawn than is applied as recharge. In the six month seasonal withdrawal about 30% more water can be withdrawn. **Figure 26** and **Figure 27** presents the minimum water levels for the simulation period for each conjunctive use scenario.

Water for the conjunctive use might be obtained from the effluent of the Yauco treatment plant or releases from Lucchetti Reservoir. The analysis of recharge sources is beyond the scope of this investigation. This study only determines whether or not recharge could provide a significant benefit.

5. CONCLUSIONS AND RECOMMENDATIONS

The Yauco alluvial aquifer model developed by this study provides a good match to the measured water levels during the calibration period (**Figure 20**), demonstrating that it can accurately replicate and simulate historical aquifer conditions. The prepared model has the limitation that it is based on approximate groundwater extraction data and thus it only approximates the real condition. Additional data should be collected and incorporated into the model to better represent current conditions.

The aquifer analysis under current conditions (Present Condition Model) shows that the aquifer is not being over-drafted. Simulations demonstrate that the aquifer could be subjected to a continuous extraction on the order of 4.6 to 4.8 mgd (1-1.25 mgd additional) without reducing the water levels to a point that could produce saltwater intrusion (**Figure 23**).

The seasonal extraction analysis demonstrates that the extraction of the aquifer could be greatly increased during the dry season, especially if artificial recharge is used. An additional 6 mgd could be extracted over a four month period every year by injecting a constant quantity of water at a rate of 1.3 mgd (**Figure 26**). If the extractions are during a six month period per year, additional 5 mgd could be extracted by injecting a constant quantity of water at a rate of 1.95 mgd (**Figure 27**).

If artificial recharge is to be practical, it should occur in the upper part of the valley, extending approximately from the location of the existing PRASA wastewater plant, upstream to a point about 1 km below PR-2.

The Yauco alluvial aquifer model can be used as a guide to analyze other aquifers in the area. There are various zones along the South Coast Alluvial aquifer that are in critic condition and should be analyzed to evaluate different management alternatives. The Río Coamo and Río Nigua alluvial fan aquifers have been subjected to withdrawals in excess of the natural recharge rate. As consequence water levels have drop more than 20 feets in the last two decades resulting in water levels below sea level which can cause saltwater contamination of wells.

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FIGURES

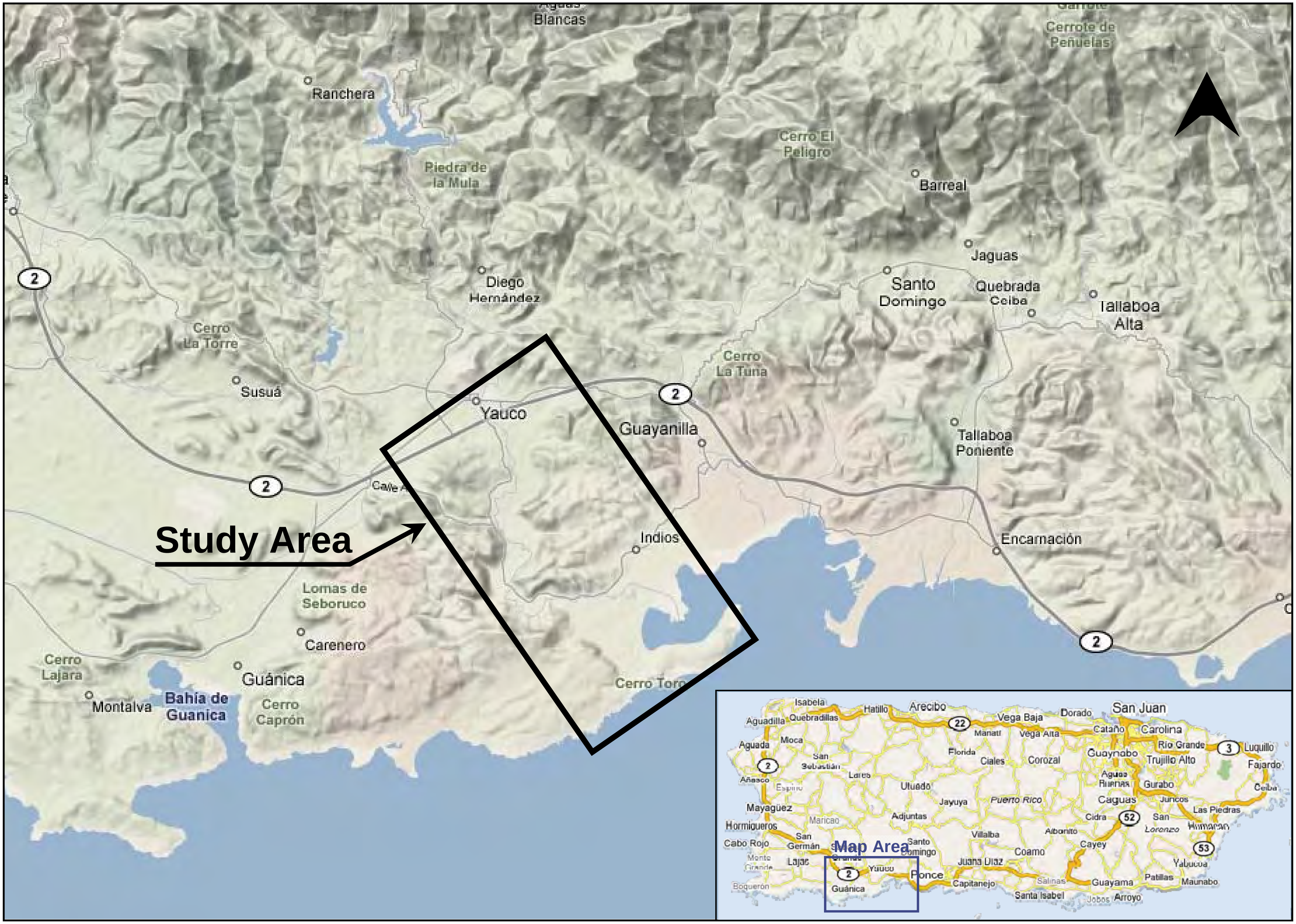

Figure 1: Location and limits of the study area.

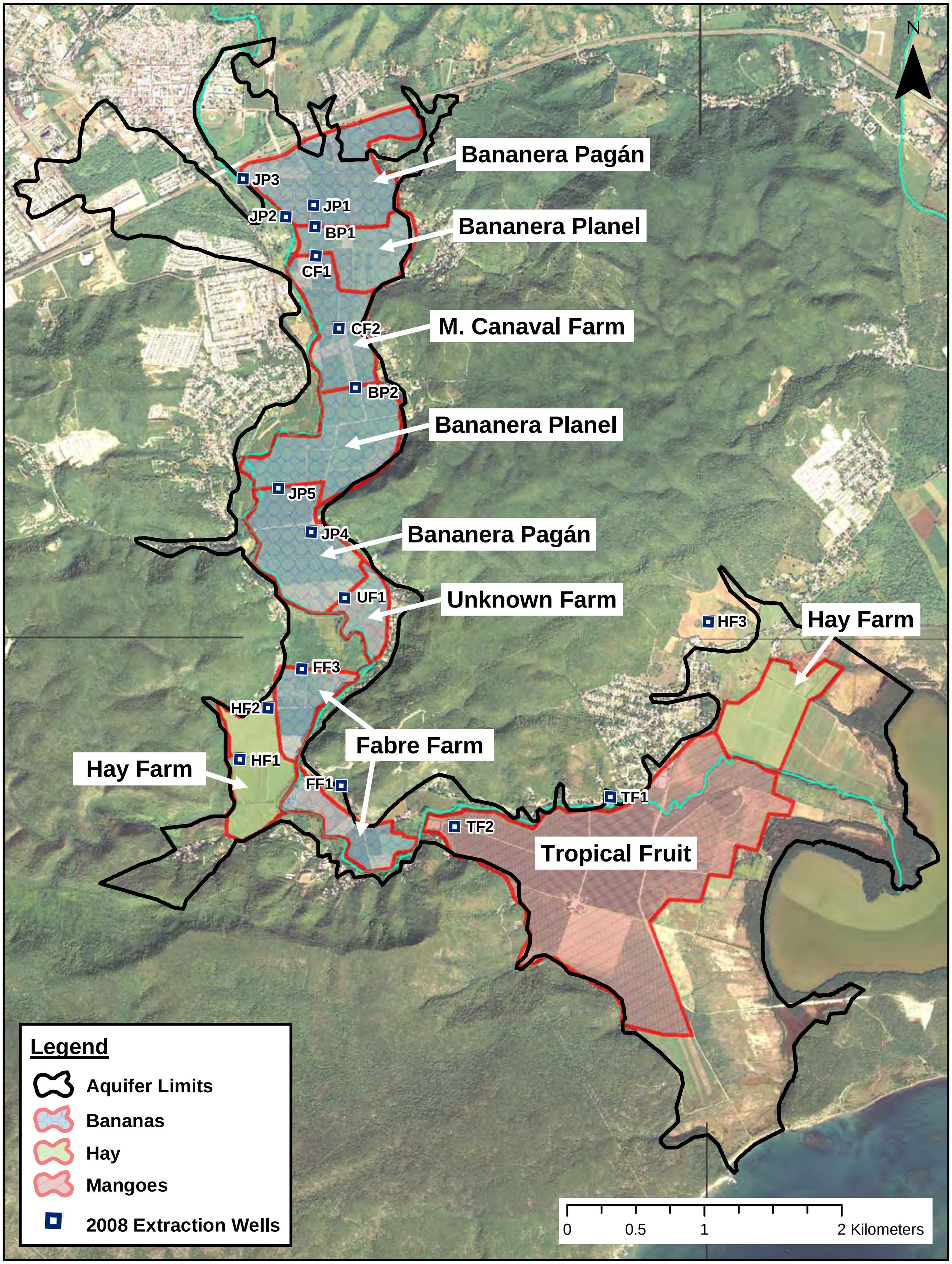

Figure 2: Present land use of the Yauco Alluvial Valley and current extraction wells.

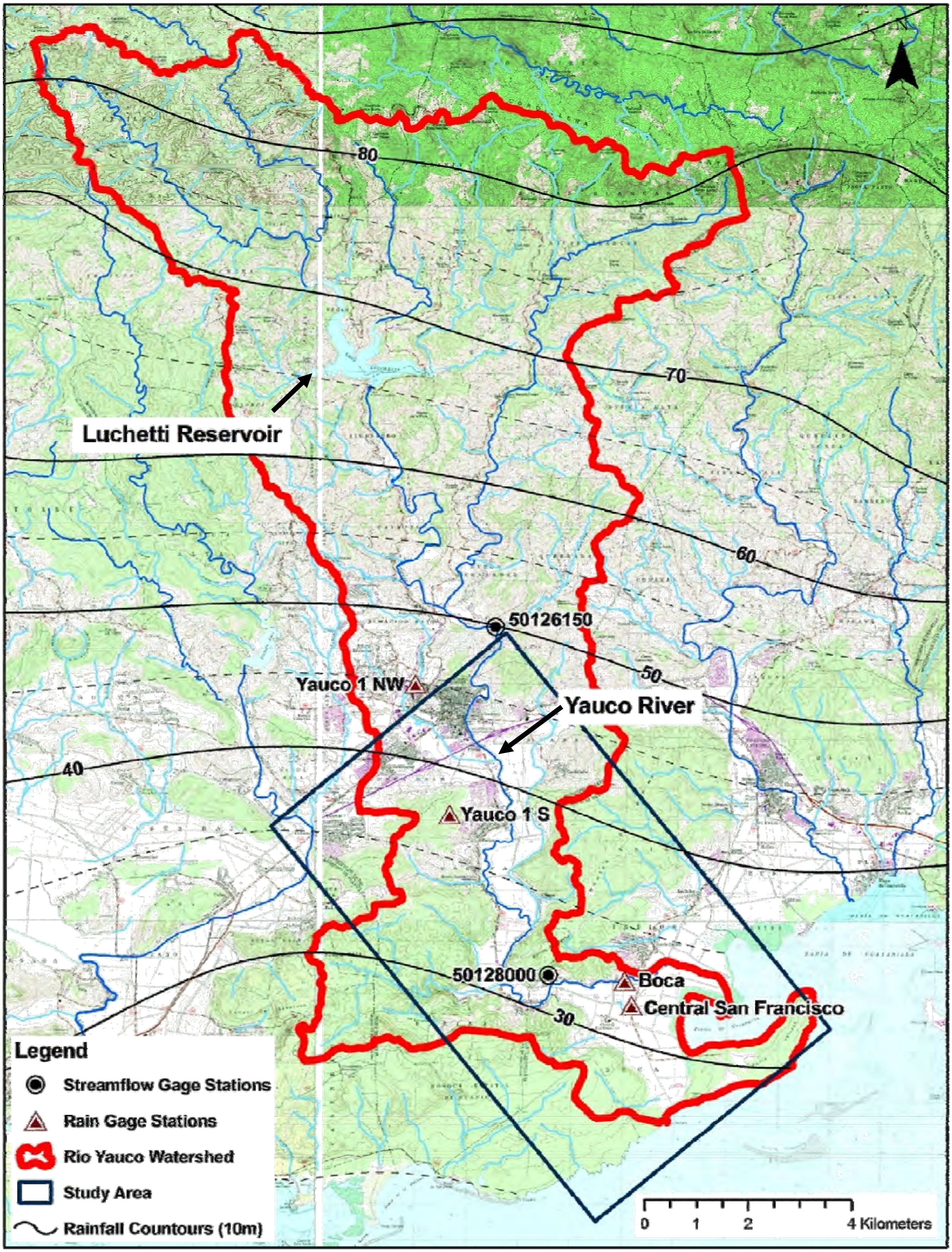

Figure 3: Study area location and hydrologic features.

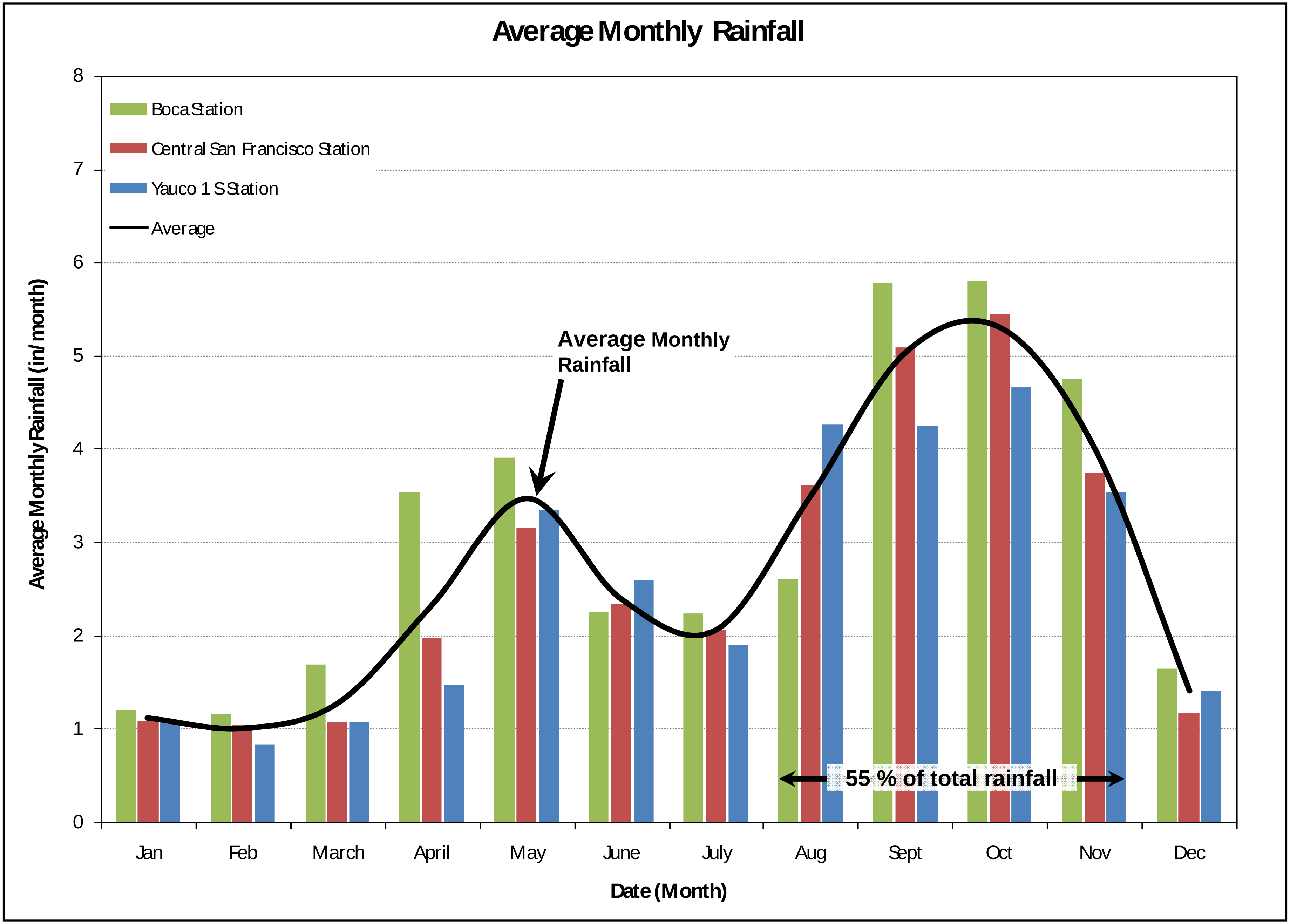

Figure 4: Mean monthly rainfall variation for each rain gage in the study area.

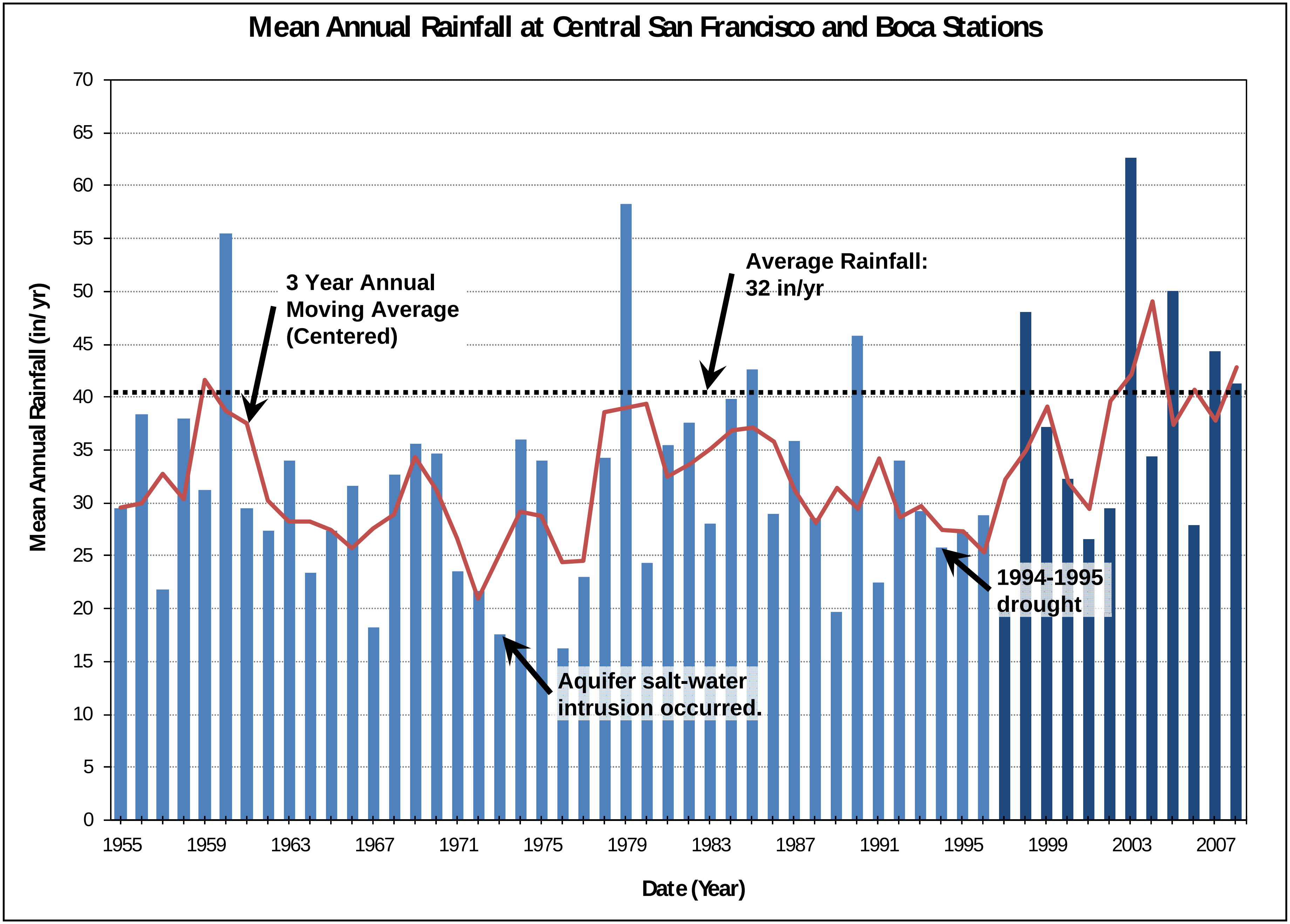

Figure 5: Mean annual rainfall from the combined data of Central San Francisco and Boca stations.

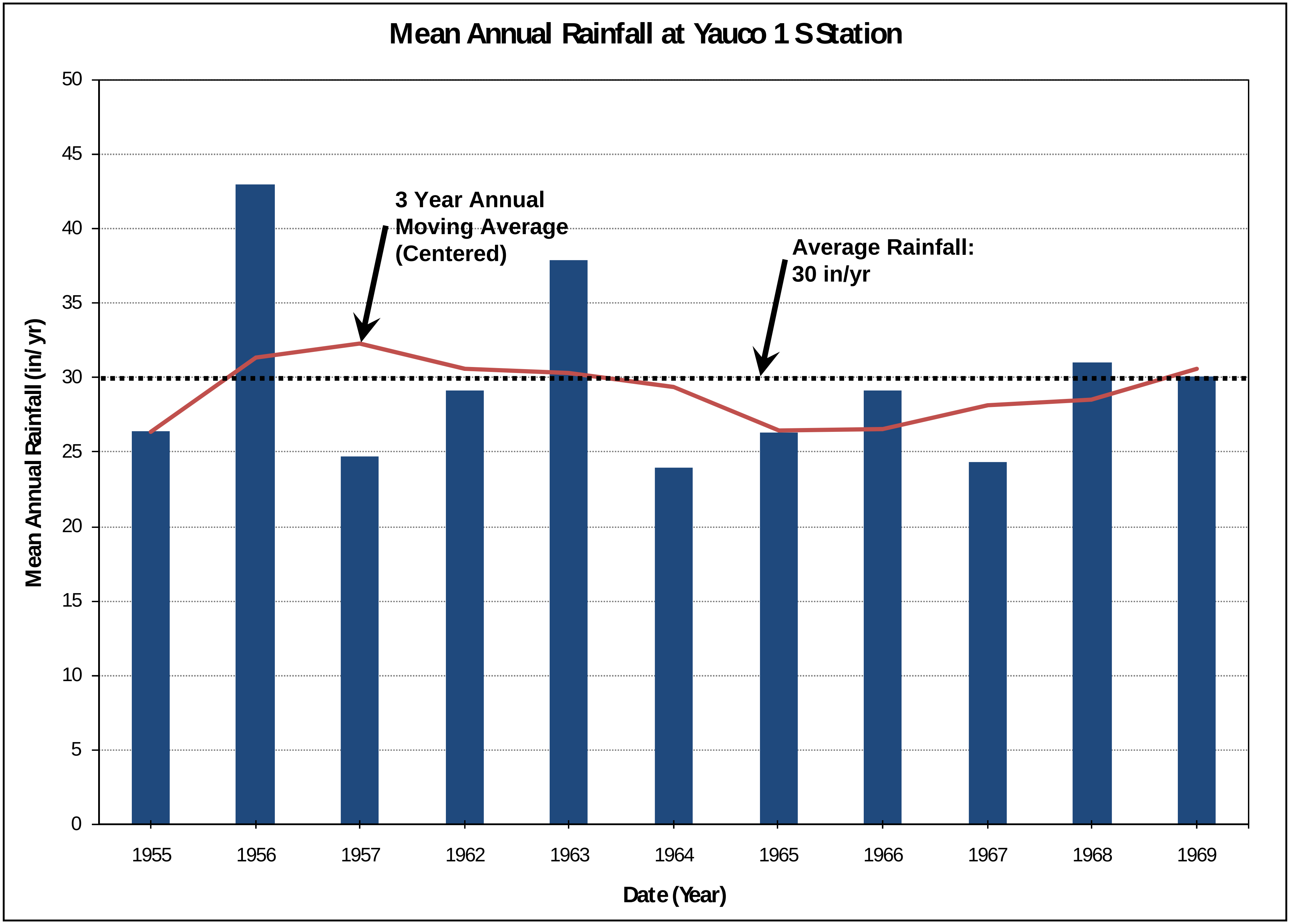

Figure 6: Mean annual rainfall at Yauco 1 S station.

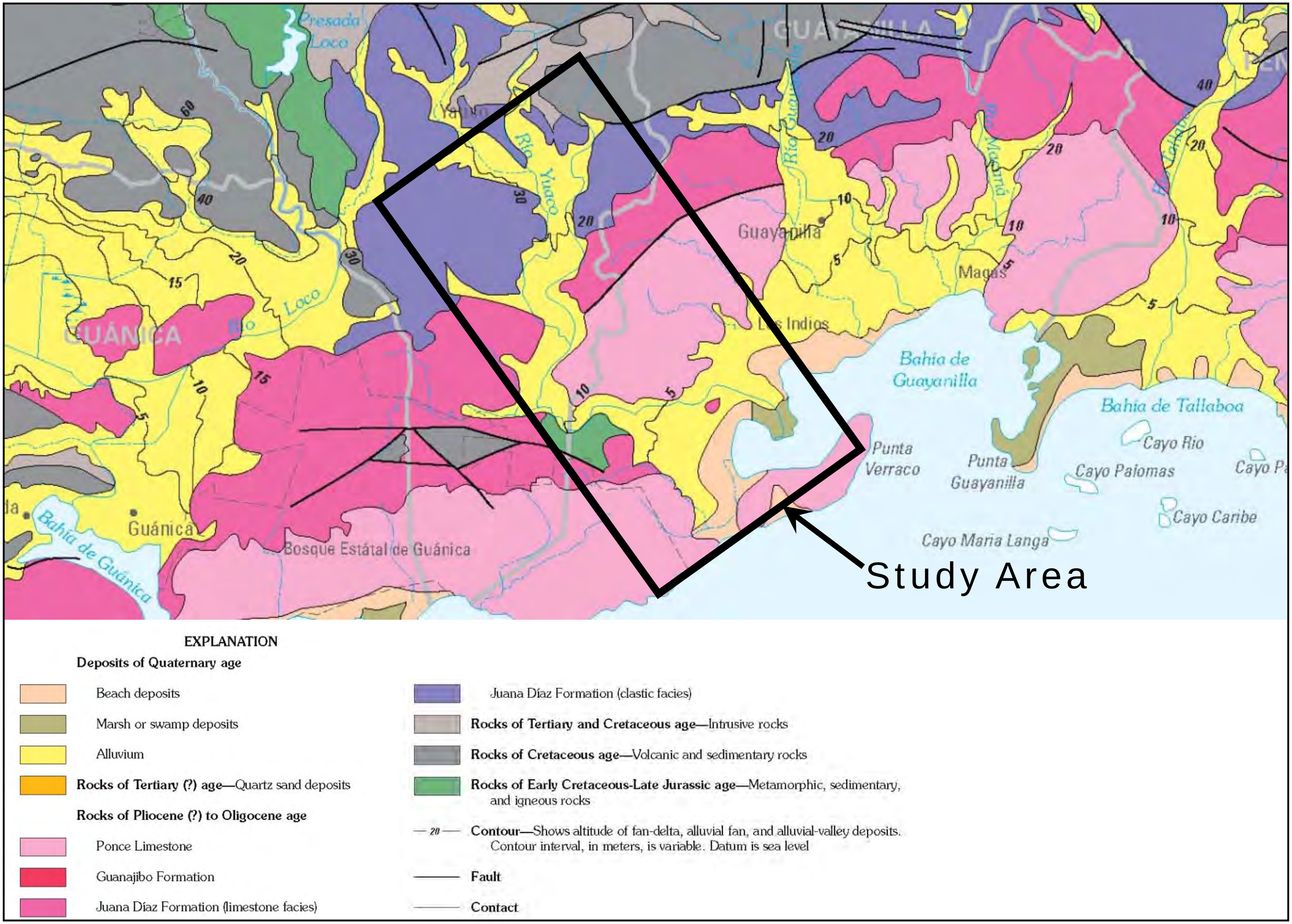

Figure 7: Principal features of the Yauco area, including the limits of the study area (modified from Renken and others, 2000).

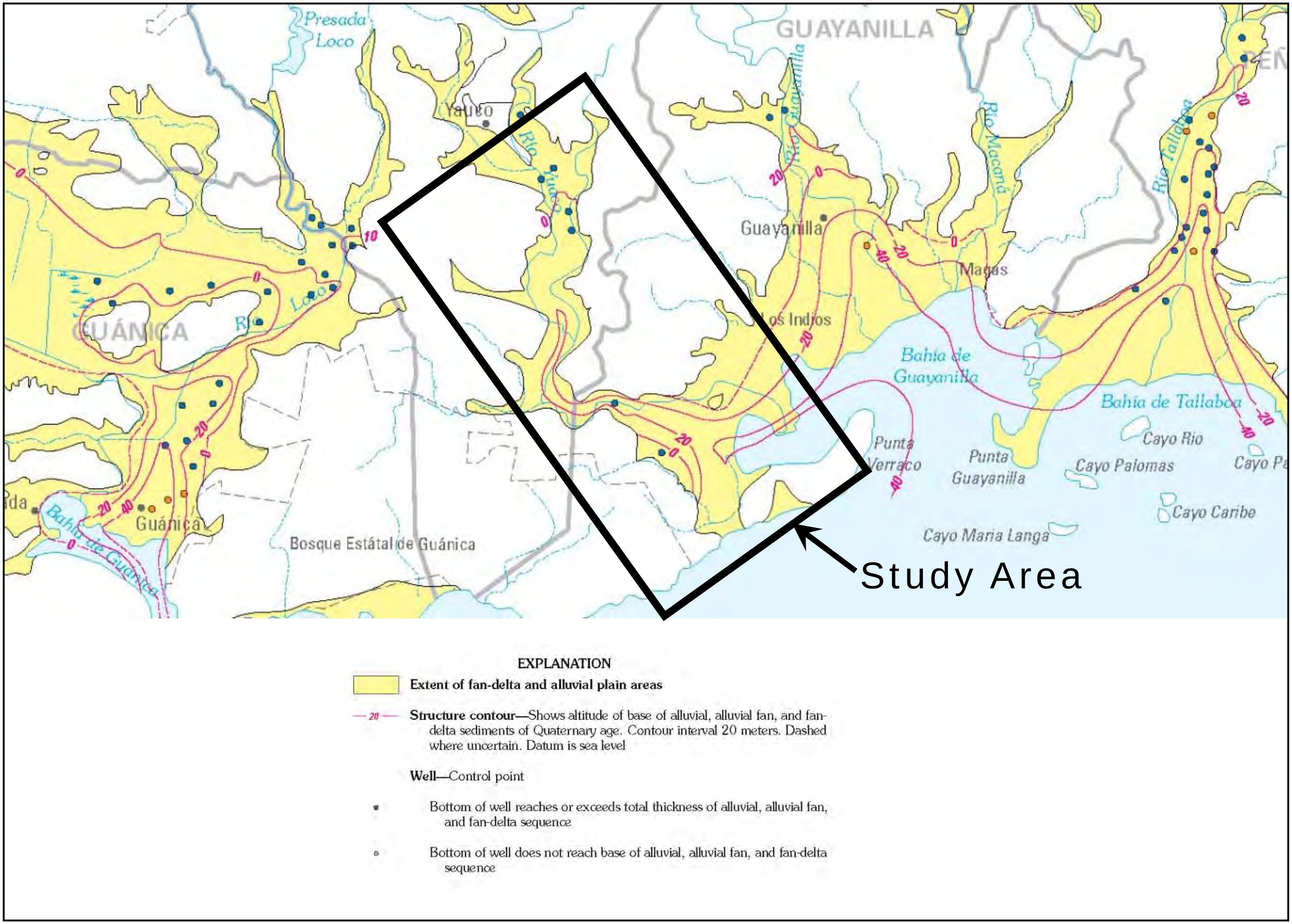

Figure 8: Base elevation of the alluvium (modified from Renken and others, 2000).

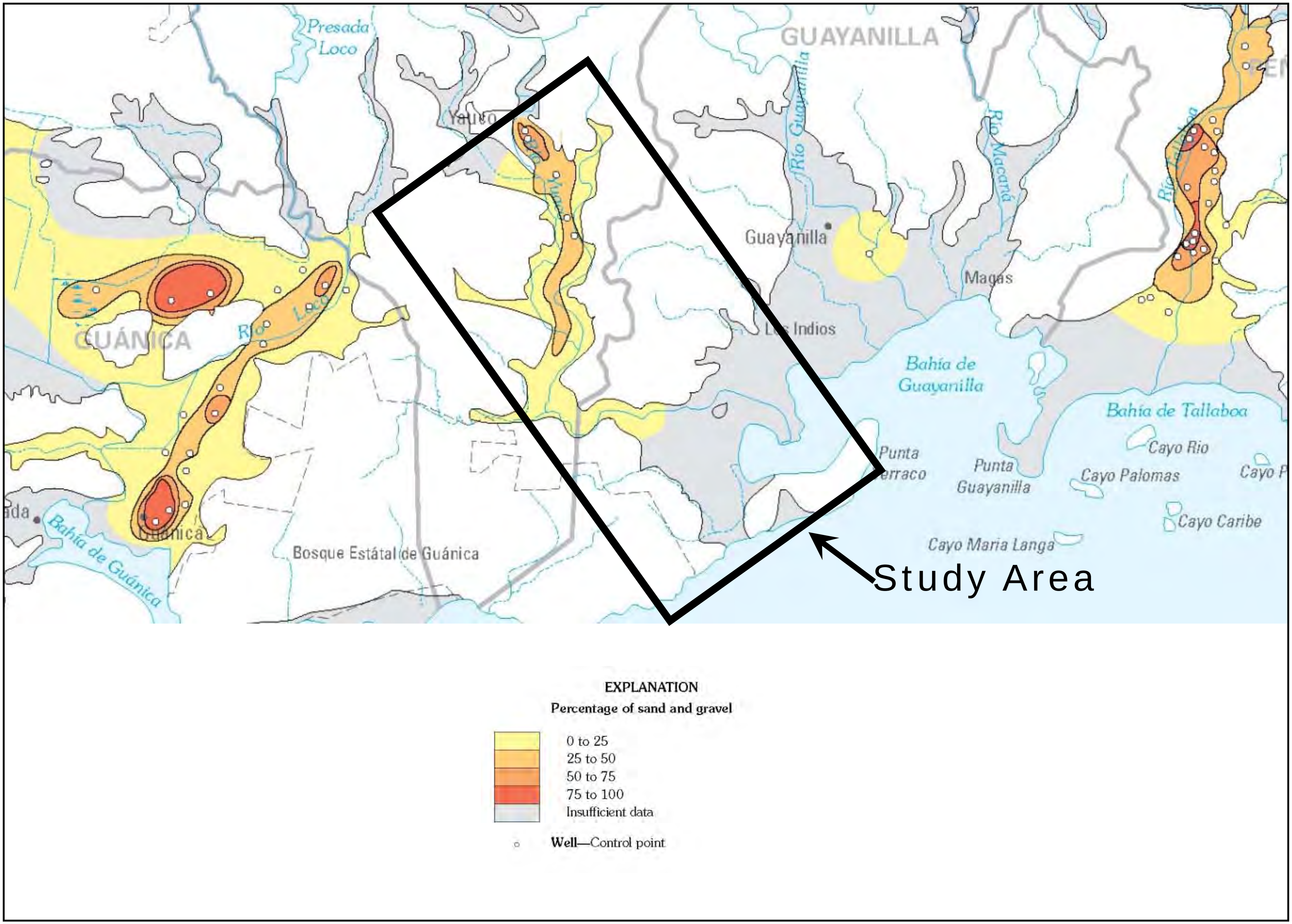

Figure 9: Sand and gravel percent along Río Yauco alluvial valley. (modified from Renken and others, 2000).

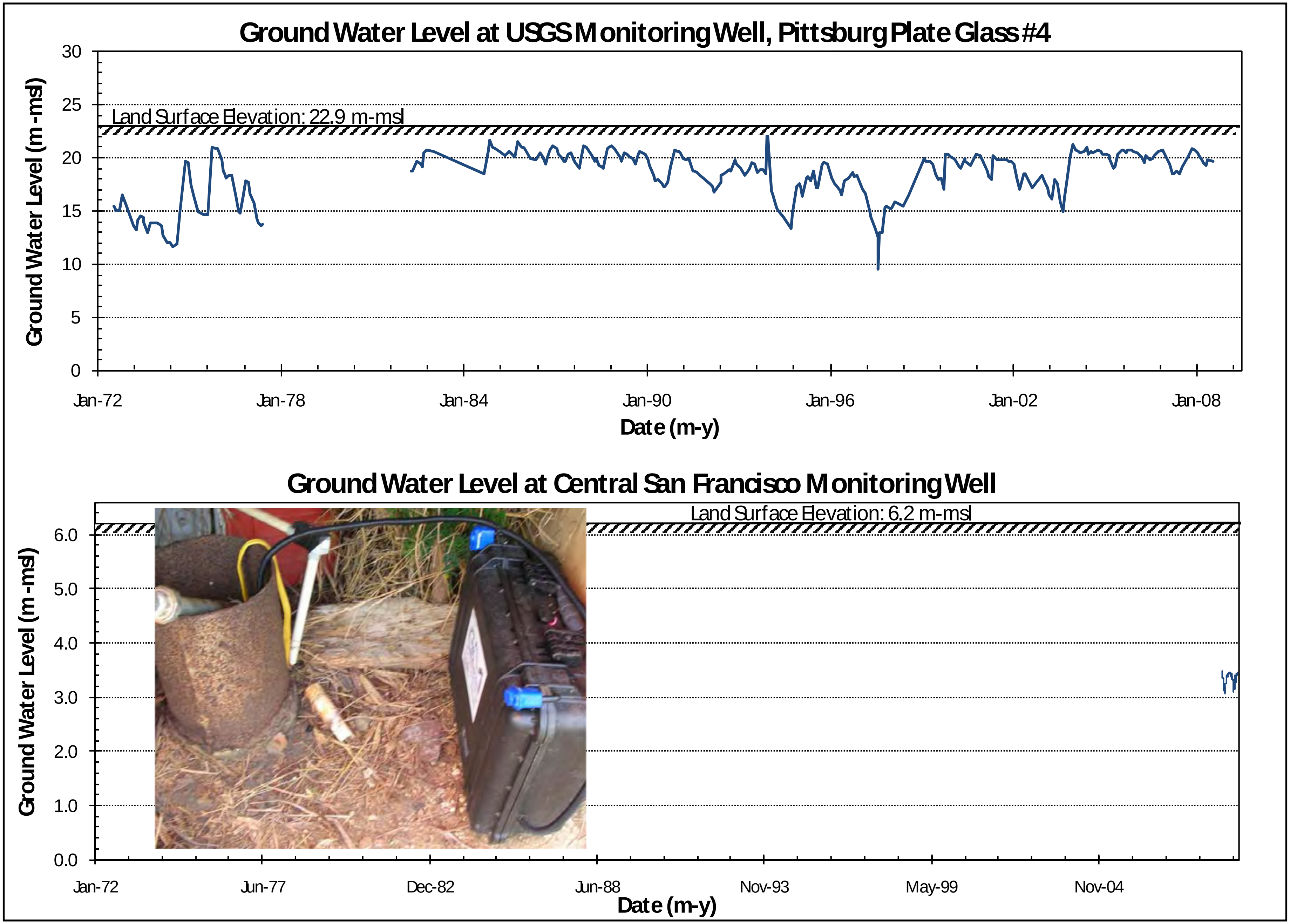

Figure 10: Water levels of the Yauco Alluvial Aquifer at Pittsburg Plate Glass #4 and Central San Francisco monitoring wells.

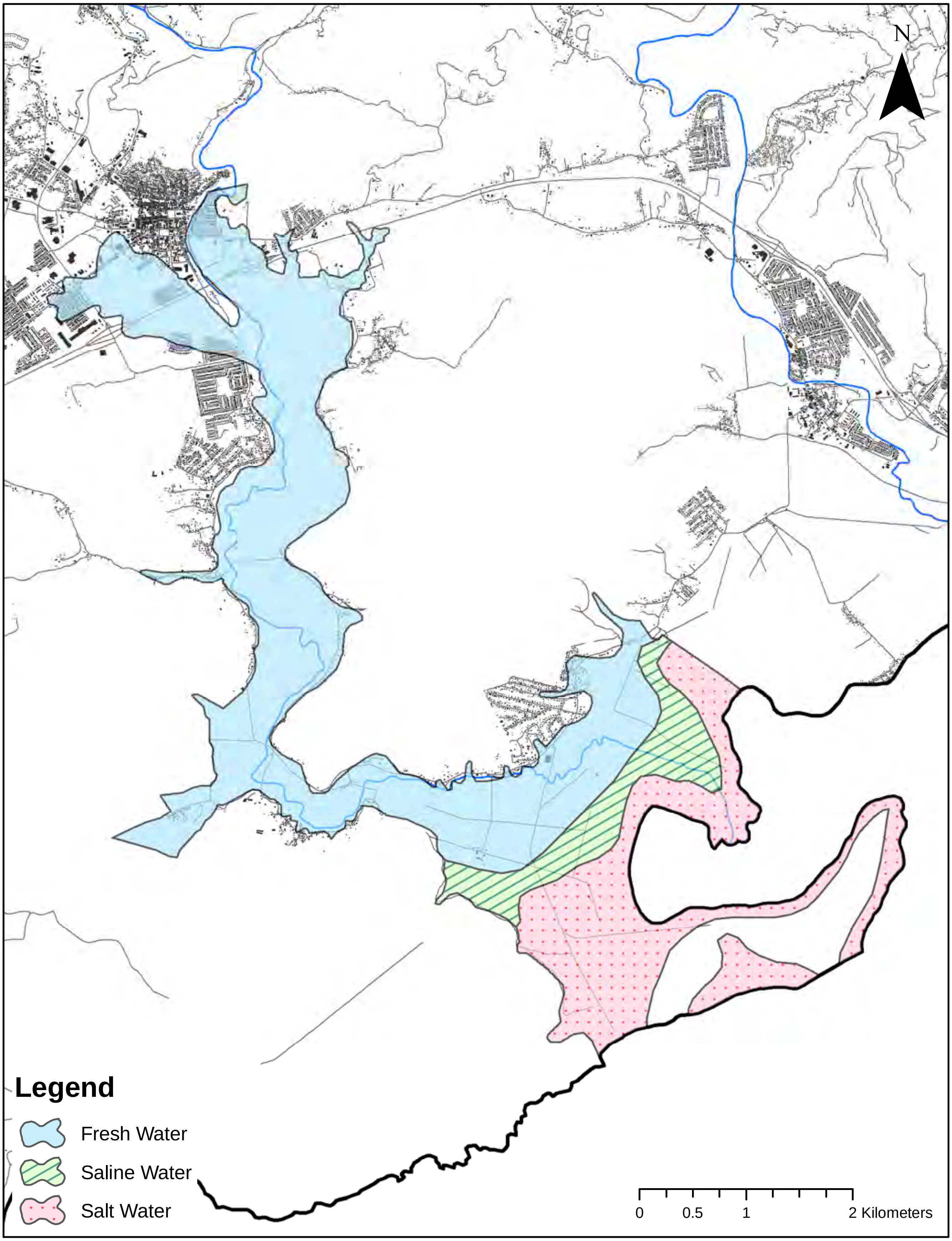

Figure 11: Saltwater intrusion limits (modified from Díaz, 1974).

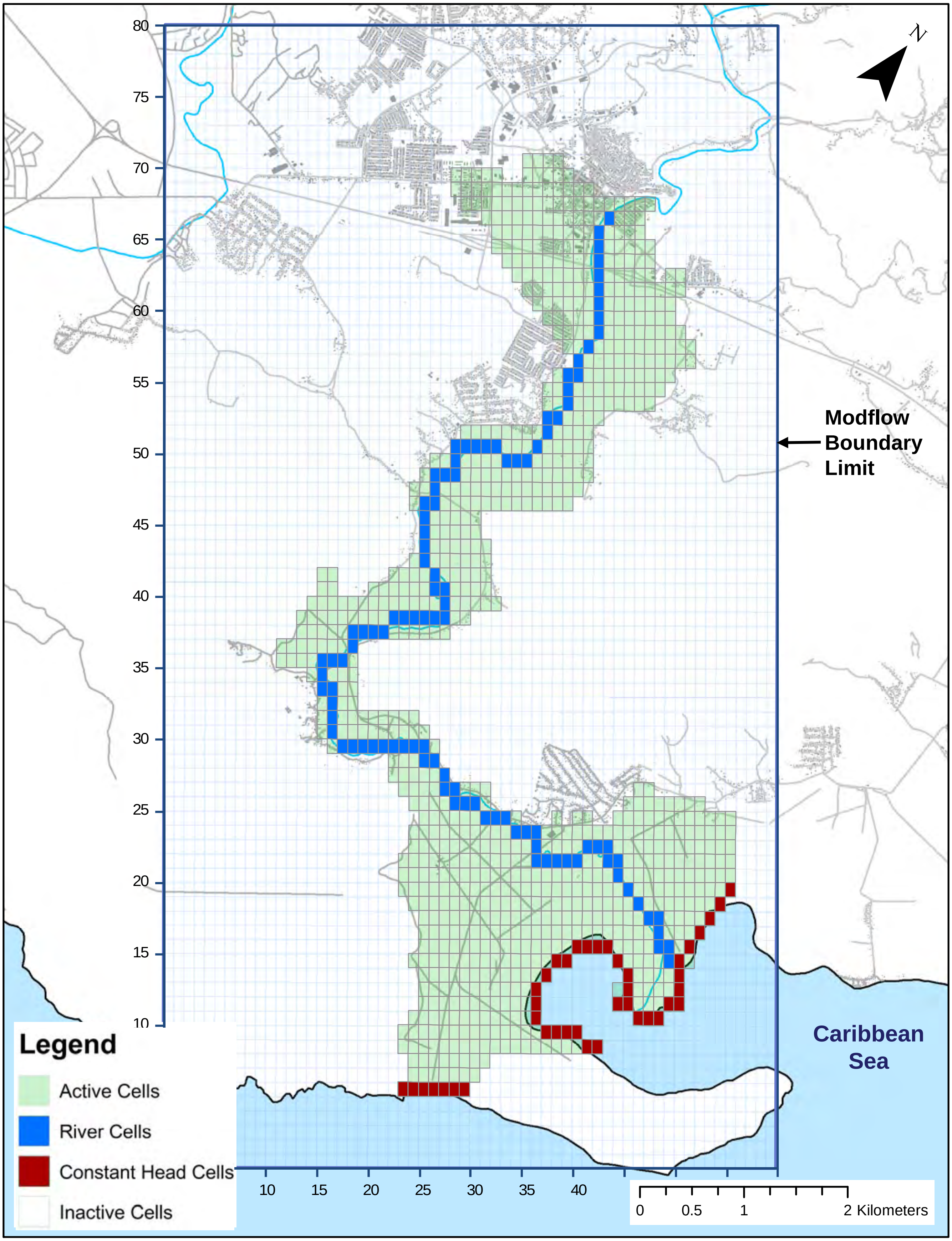

Figure 12: Groundwater flow model grid and boundary conditions.

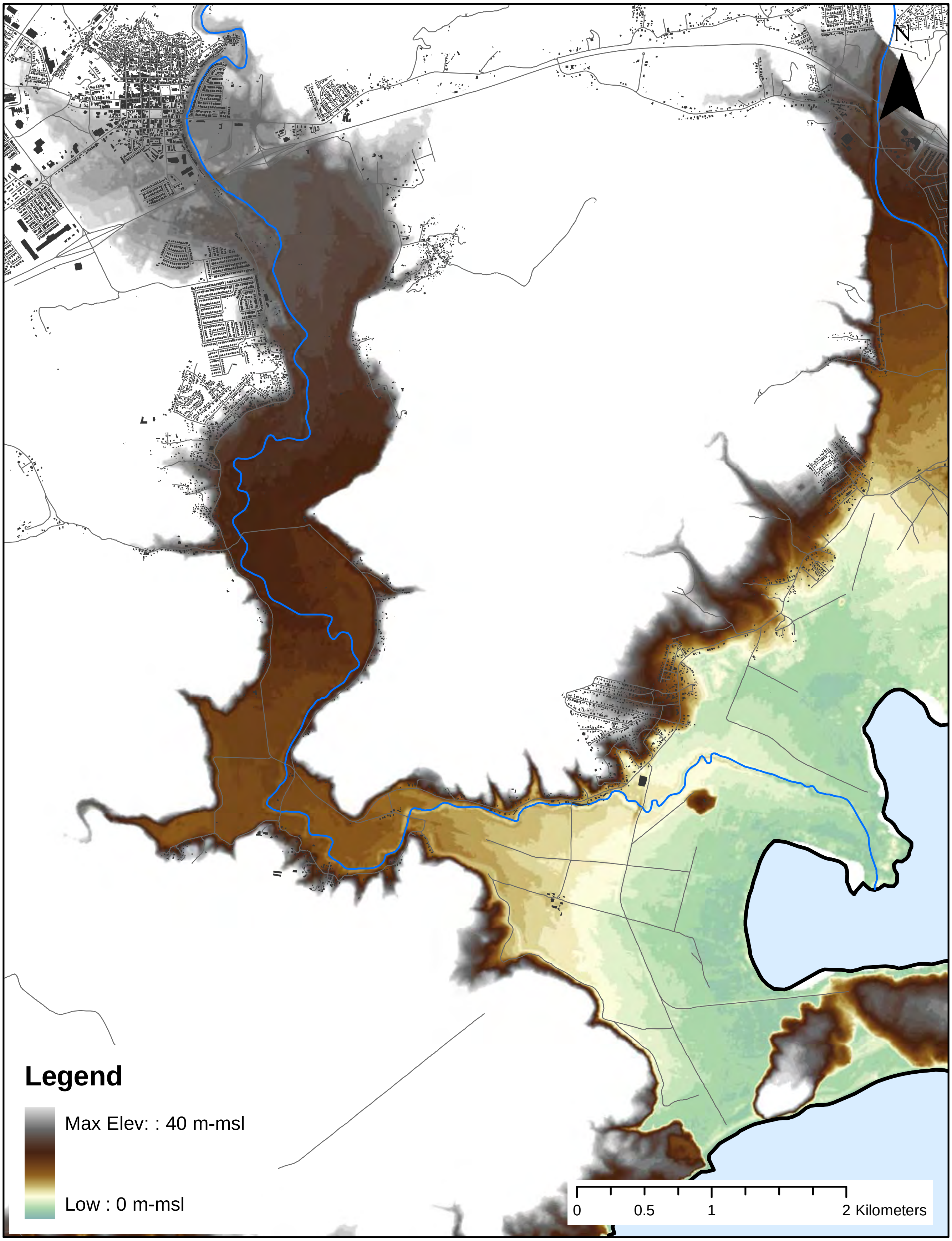

Figure 13: Puerto Rico National Elevation Dataset surface used to represent the top elevation of the grid cells.

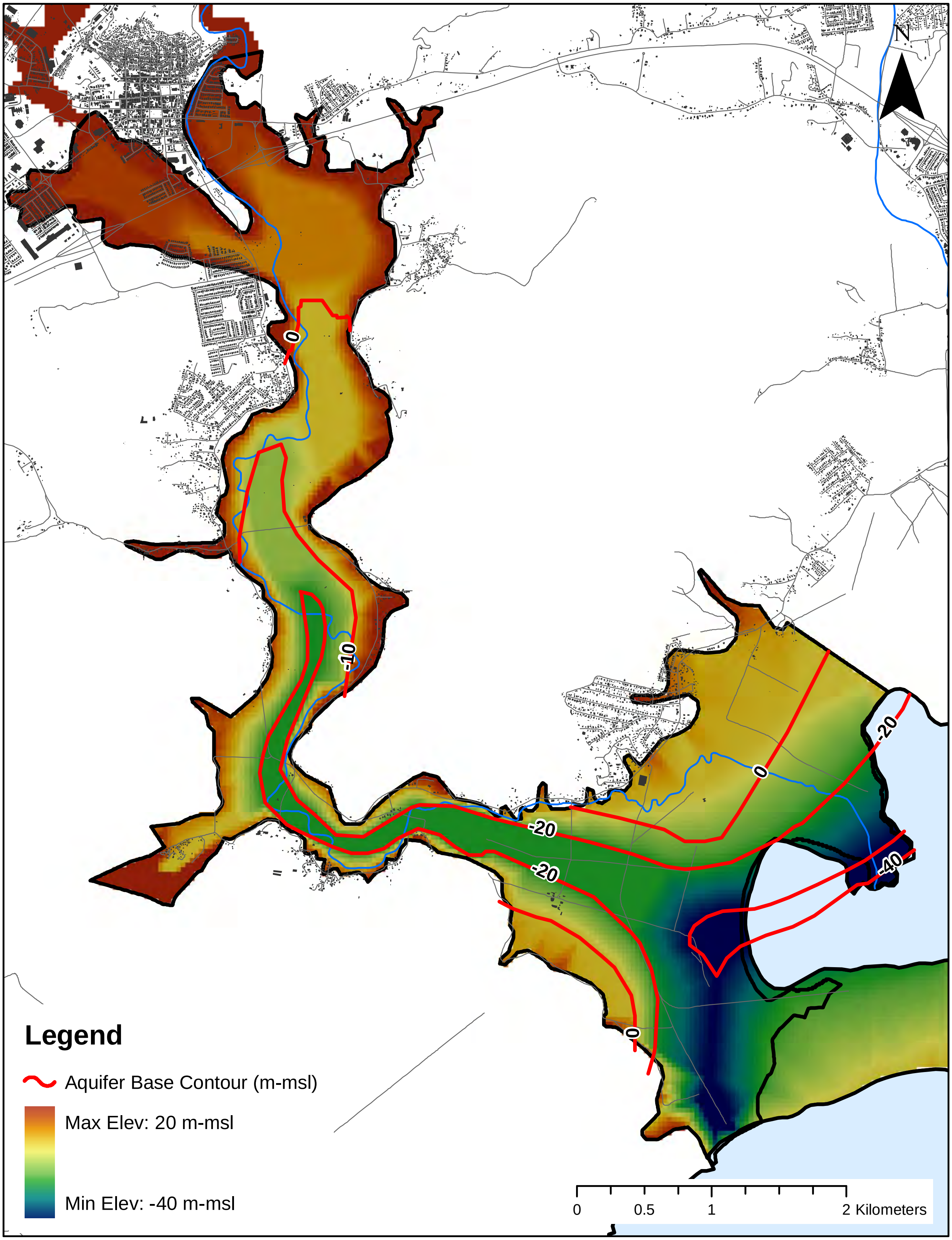

Figure 14: Aquifer bottom surface generated from the contours presented by Renken and Others (2002), used to represent the bottom elevation of the grid cells.

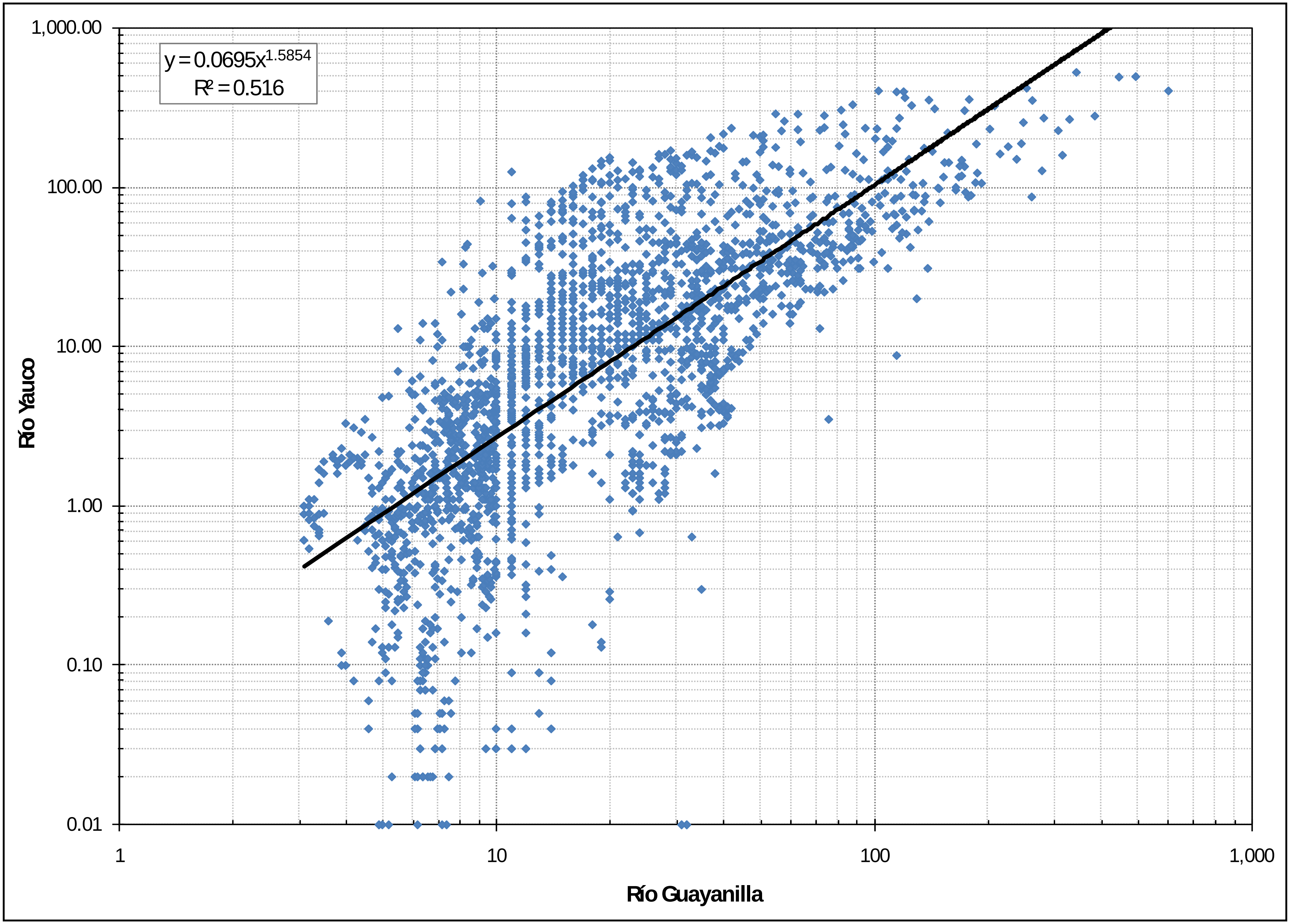

Figure 15: Streamflow relationship between Río Yauco (50126150) and Río Guayanilla (50124200) gage stations.

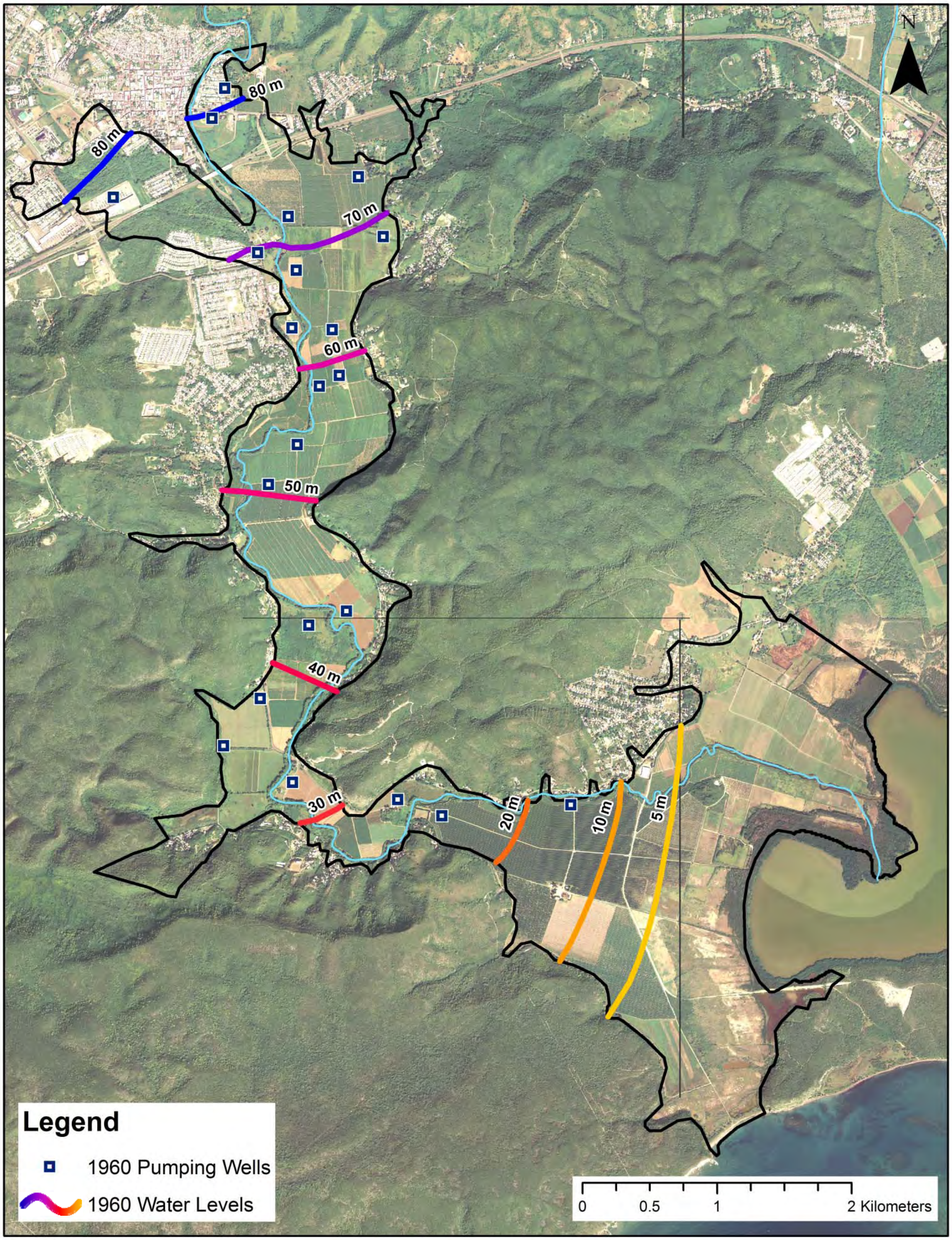

Figure 16: October, 1960 measured water levels along the Yauco Alluvial Aquifer (Quiñones-Aponte, 1986).

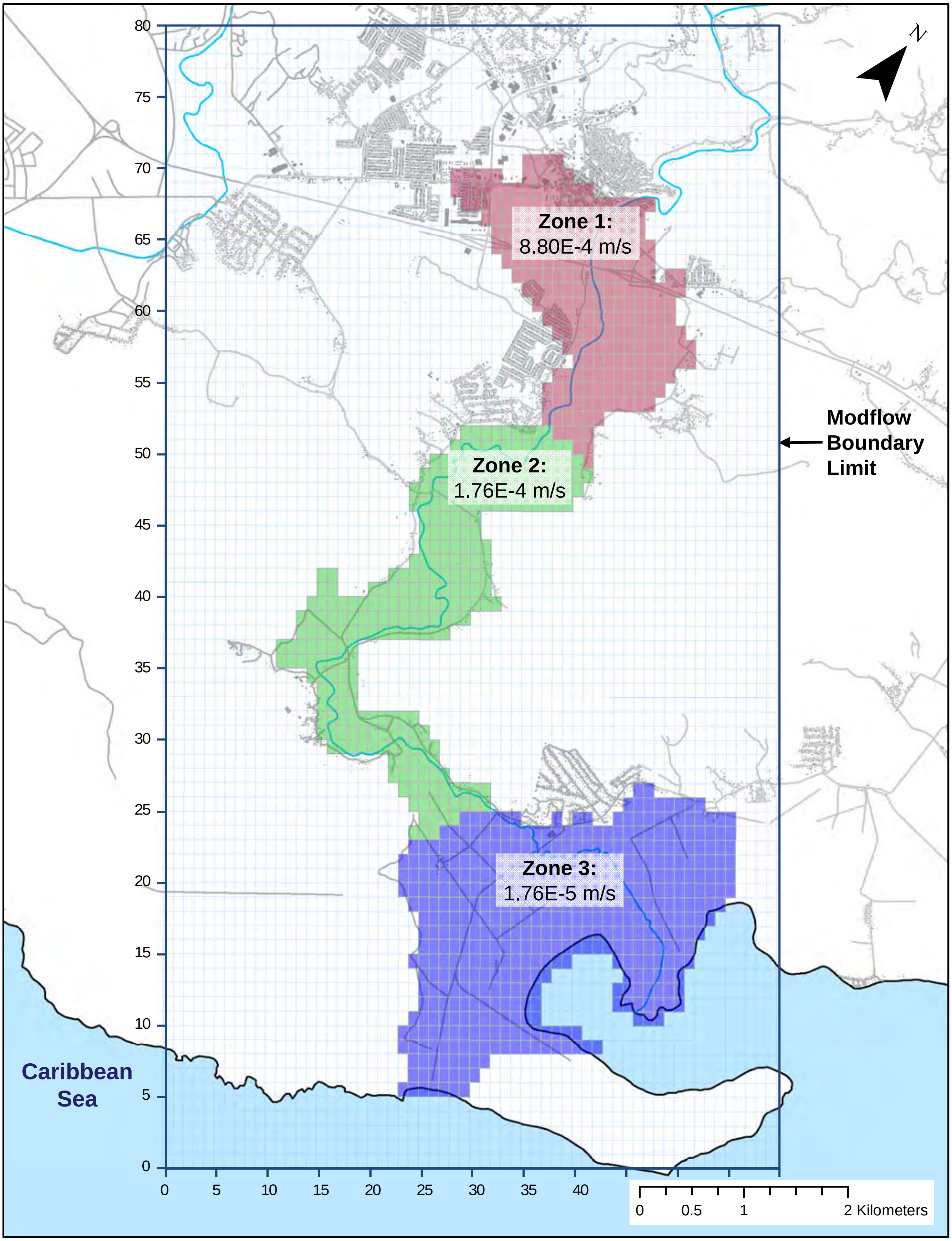

Figure 17: Calibrated hydraulic conductivity of the Yauco Alluvial Aquifer.

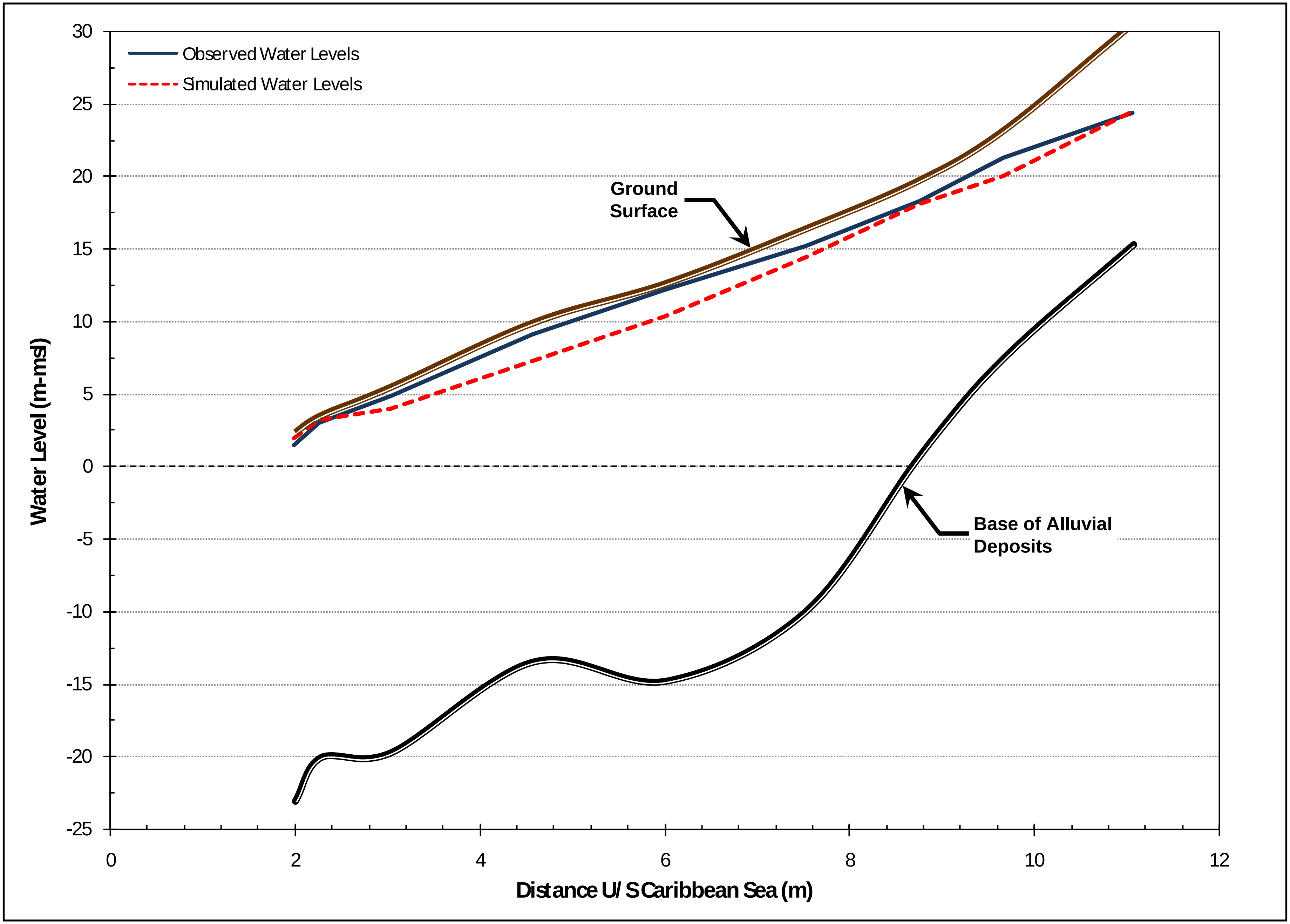

Figure 18: Comparison of simulated and observed water levels during October, 1960, steady state simulation.

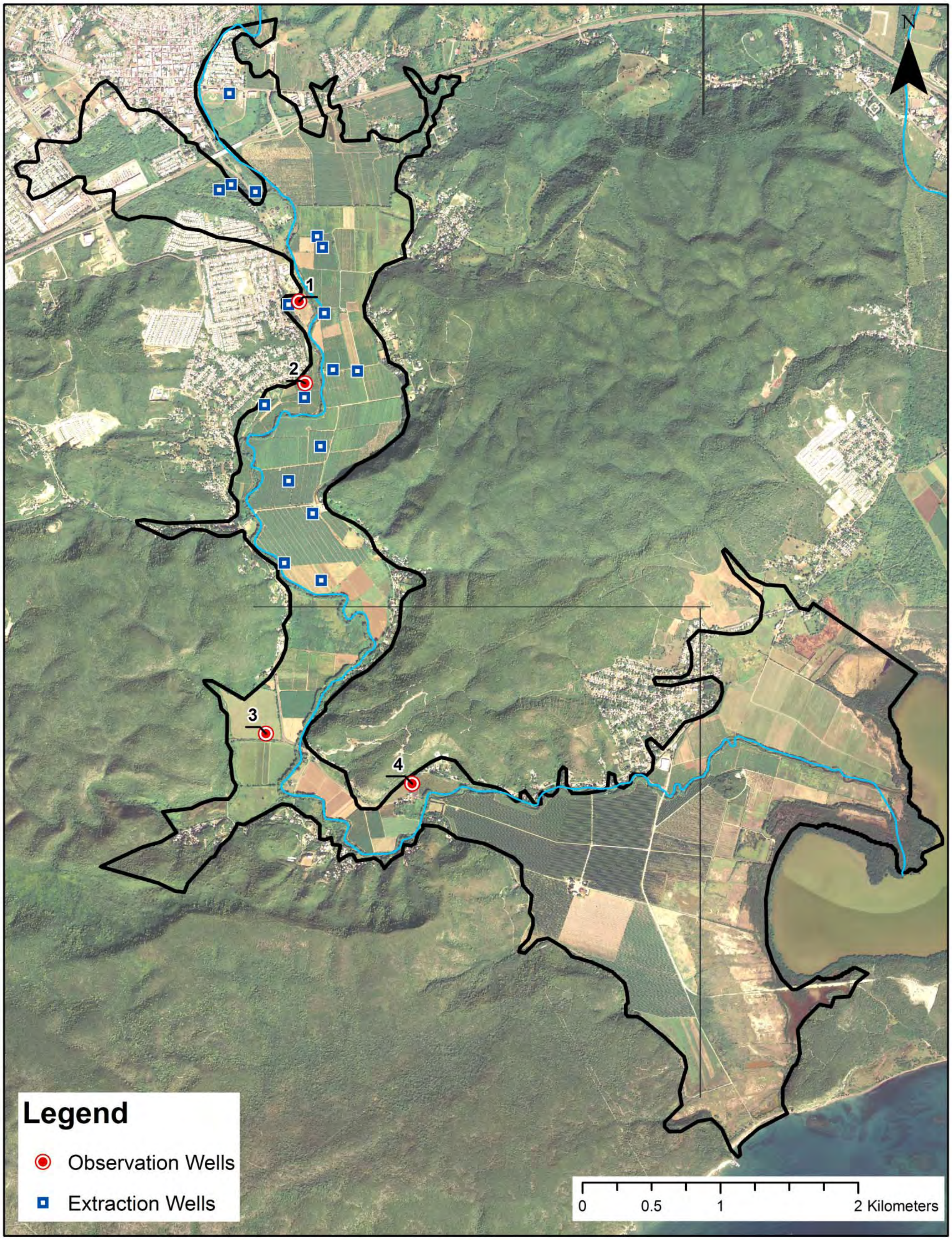

Figure 19: Location of extraction and monitoring wells during transient calibration period, 1979-1984 (Quiñones-Aponte, 1986).

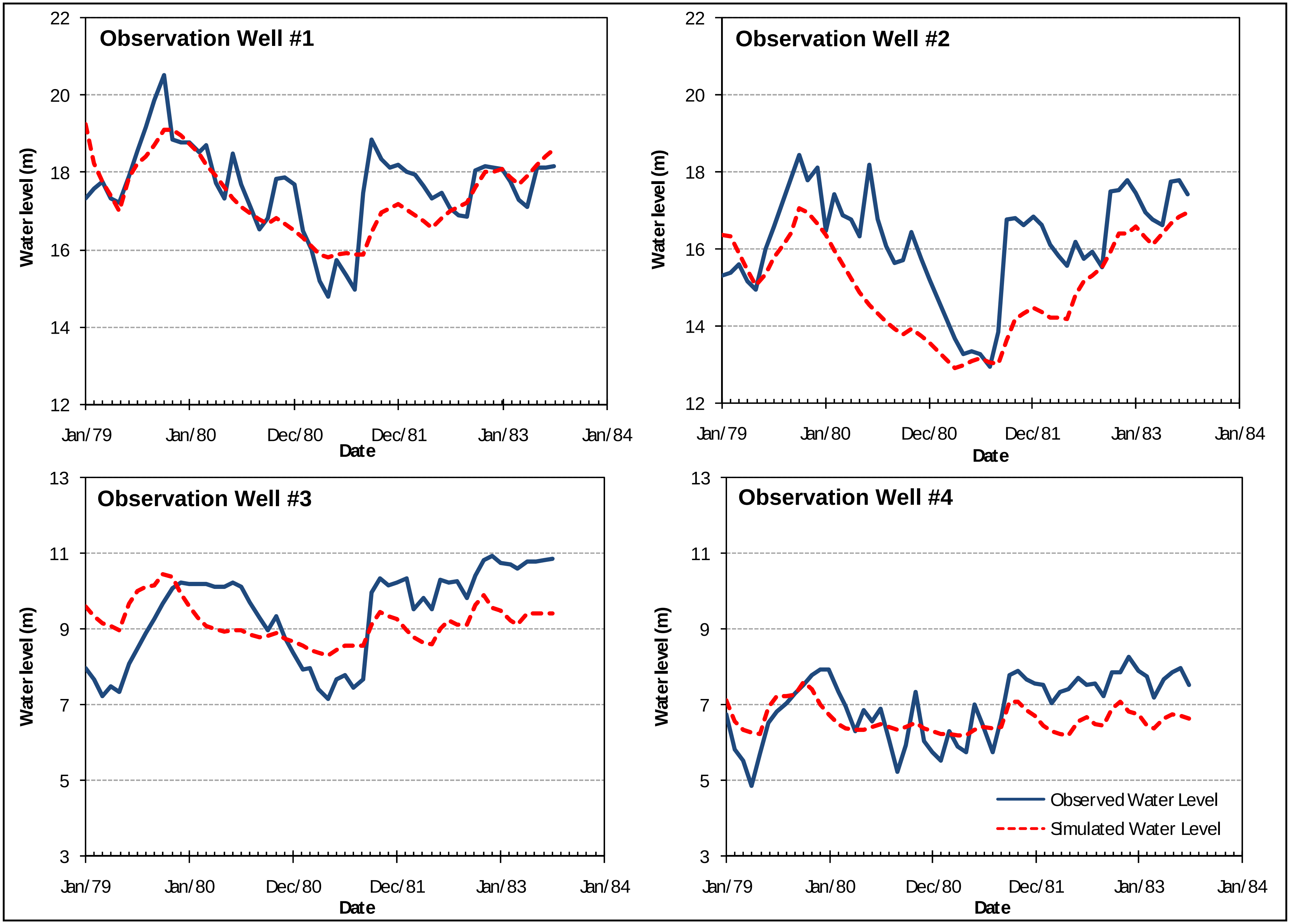

Figure 20: Comparison of simulated and observed water levels for transient calibration period (1979-1984).

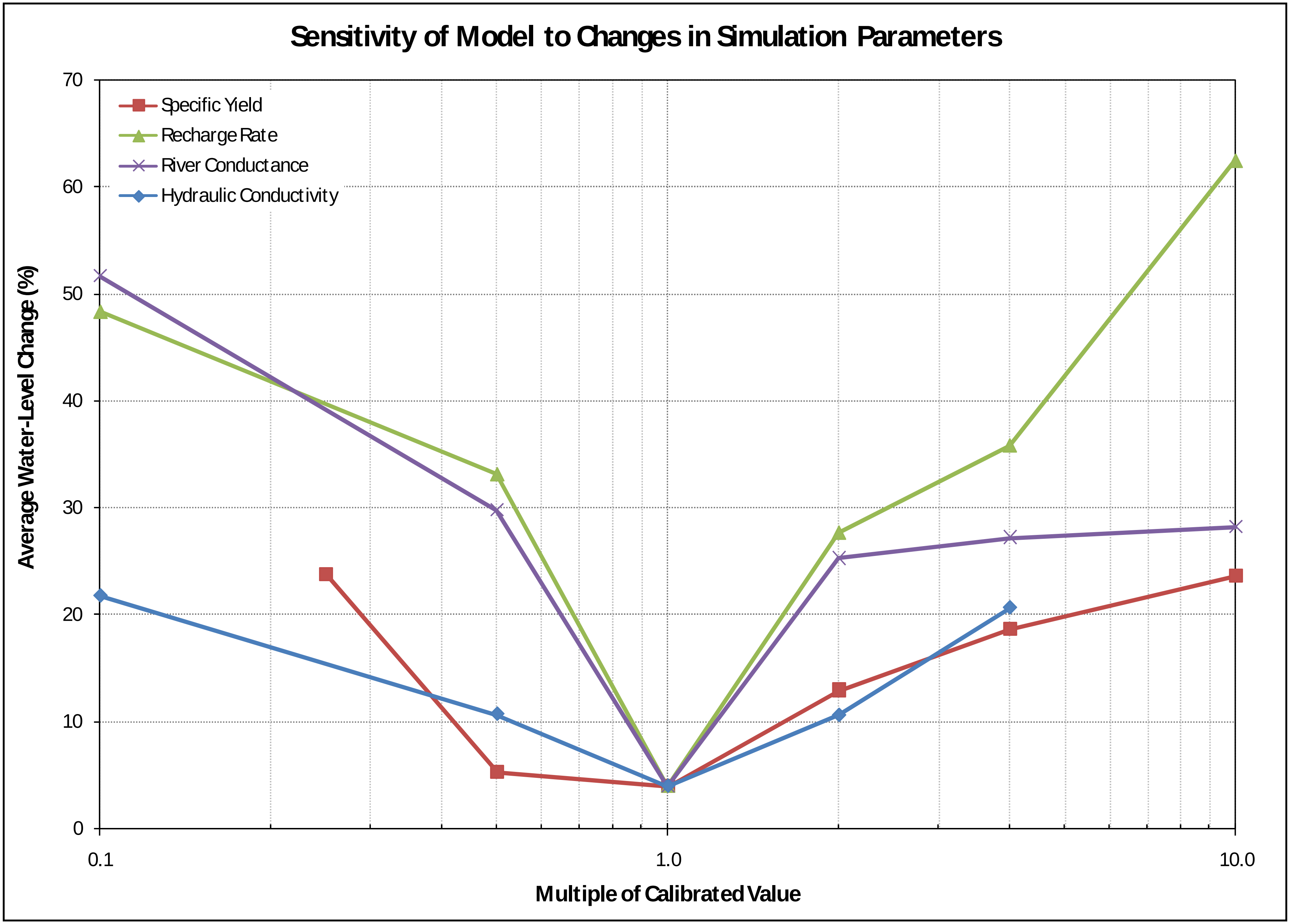

Figure 21: Sensitivity of the model to changes in simulation parameters.

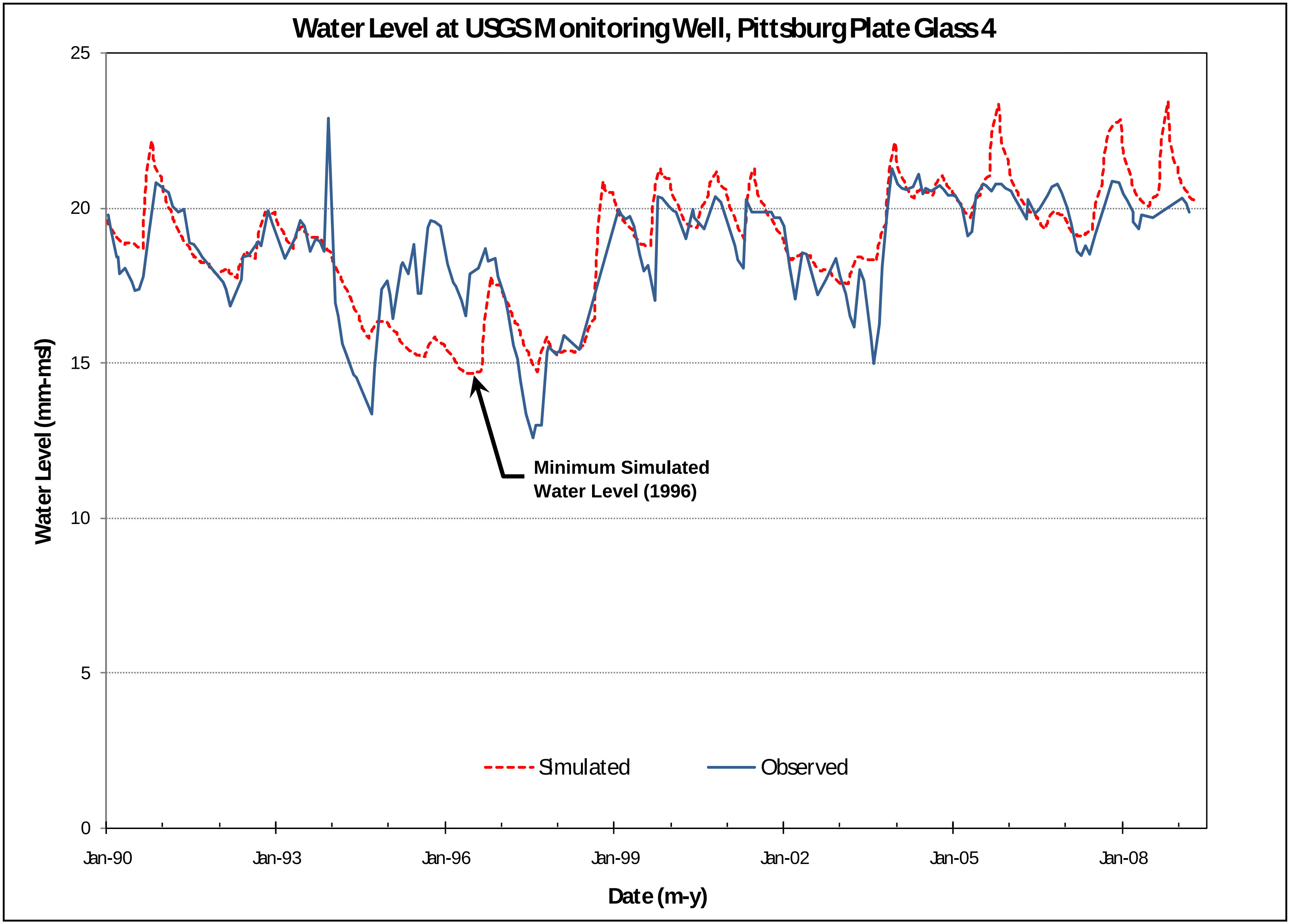

Figure 22: Comparison of observed and Present Condition Model water levels at USGS monitoring well Pittsburg Plate Glass 4, 1990-2008.

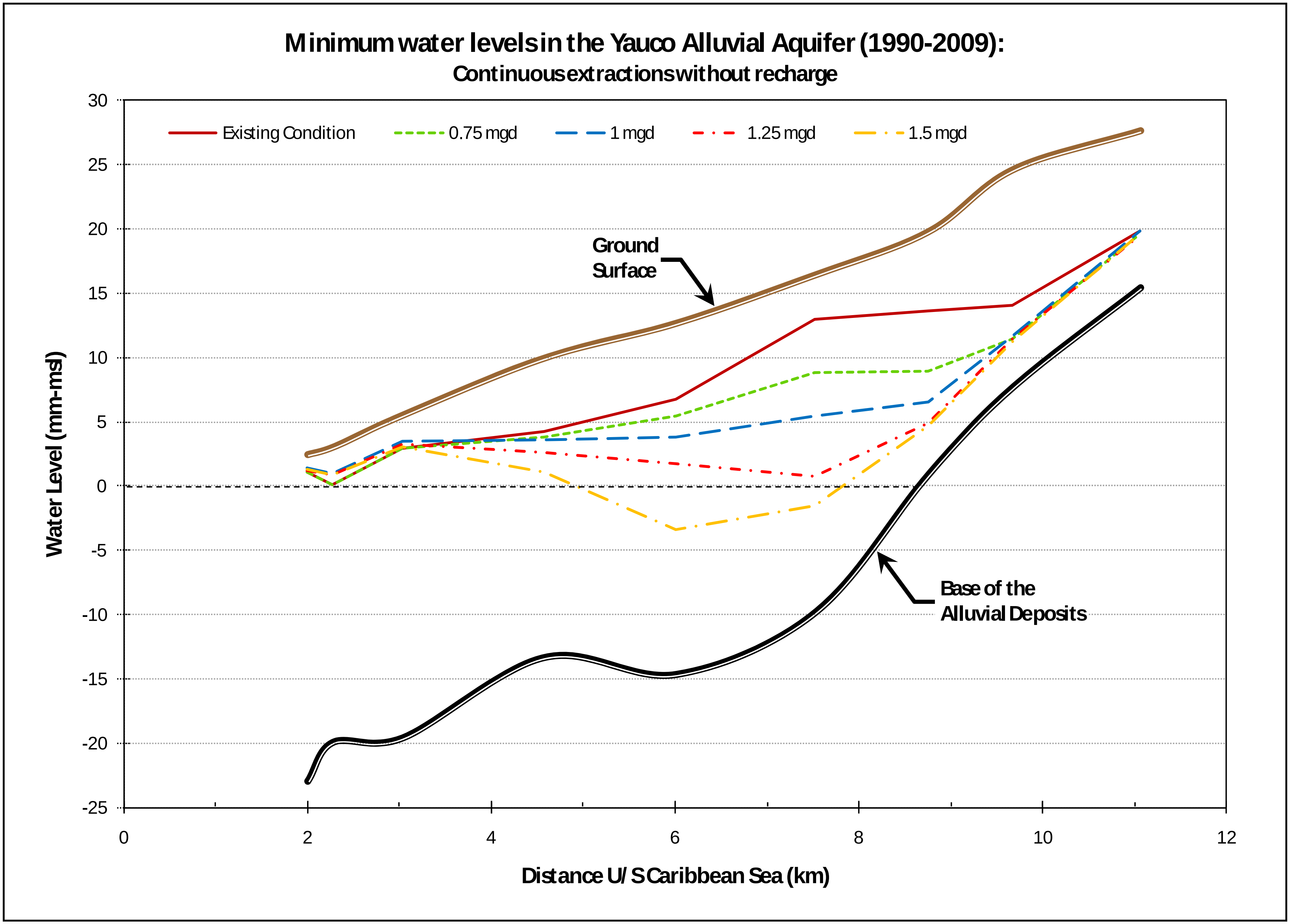

Figure 23: Present Condition Model simulated minimum water profile for current and additional continuous extractions in the Yauco Alluvial Aquifer, 1990-2008.

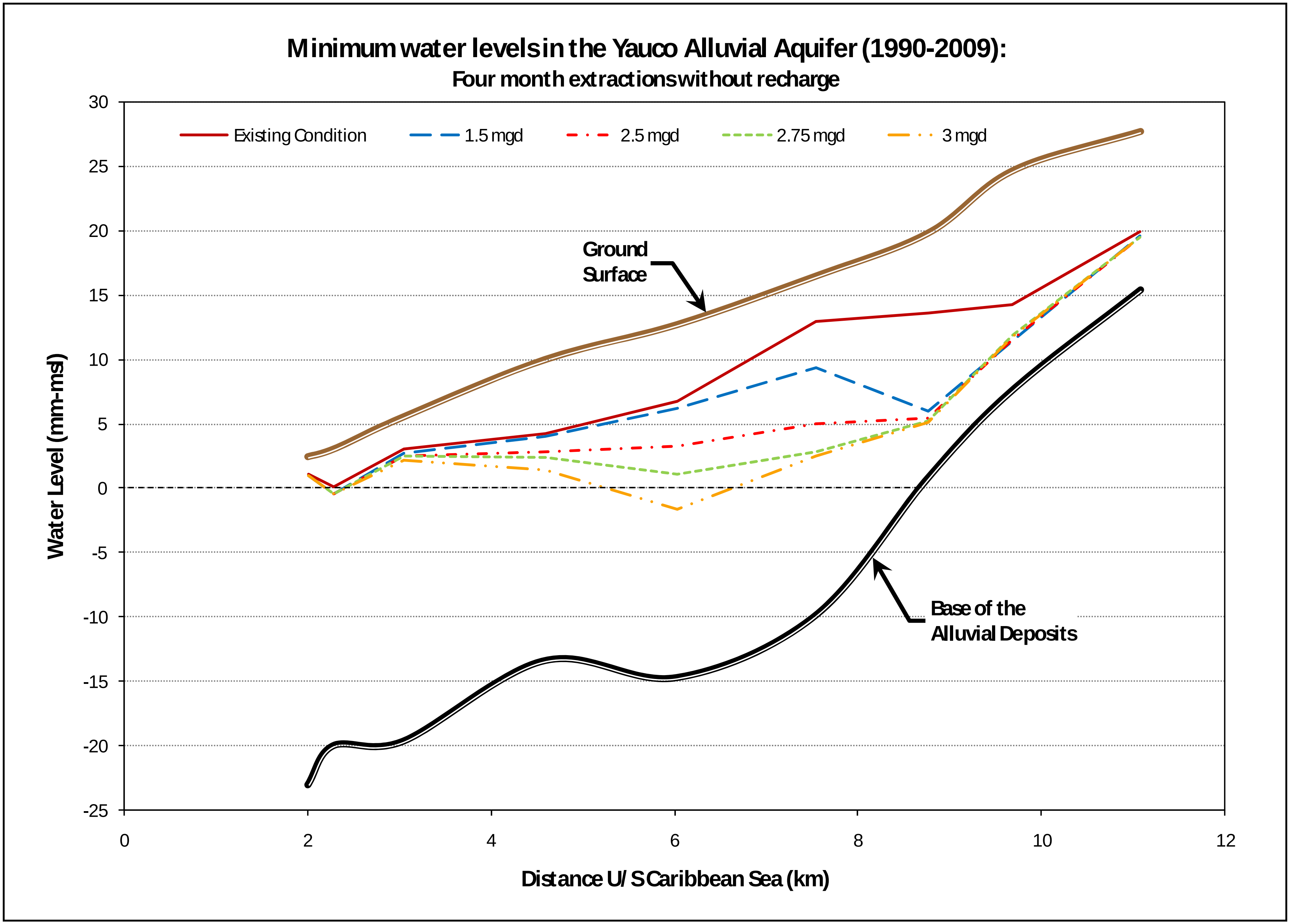

Figure 24: Present Condition Model simulated minimum water profile for current and additional four month extractions in the Yauco Alluvial Aquifer, 1990-2008.

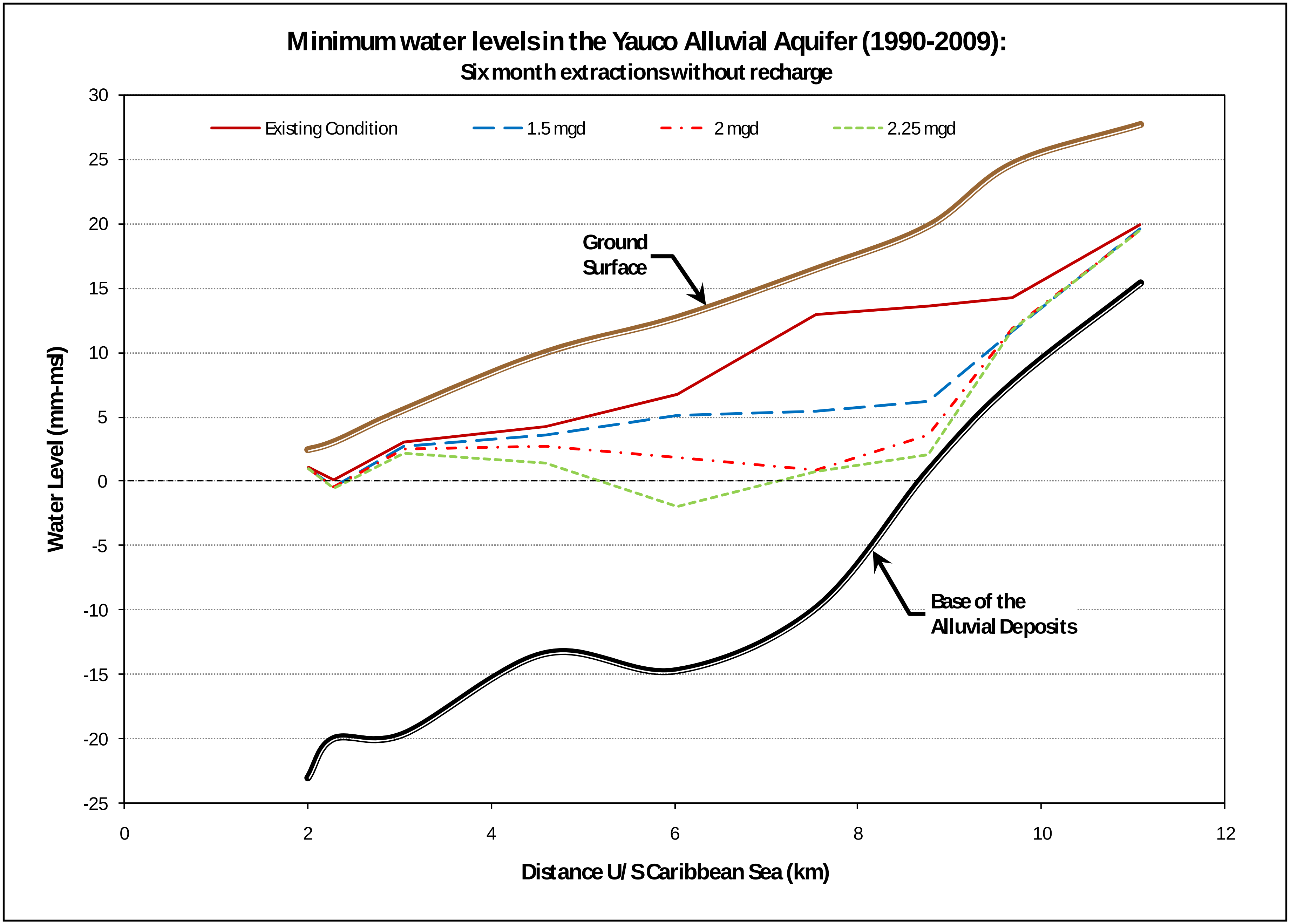

Figure 25: Present Condition Model simulated minimum water profile for current and additional six month extractions in the Yauco Alluvial Aquifer, 1990-2008.

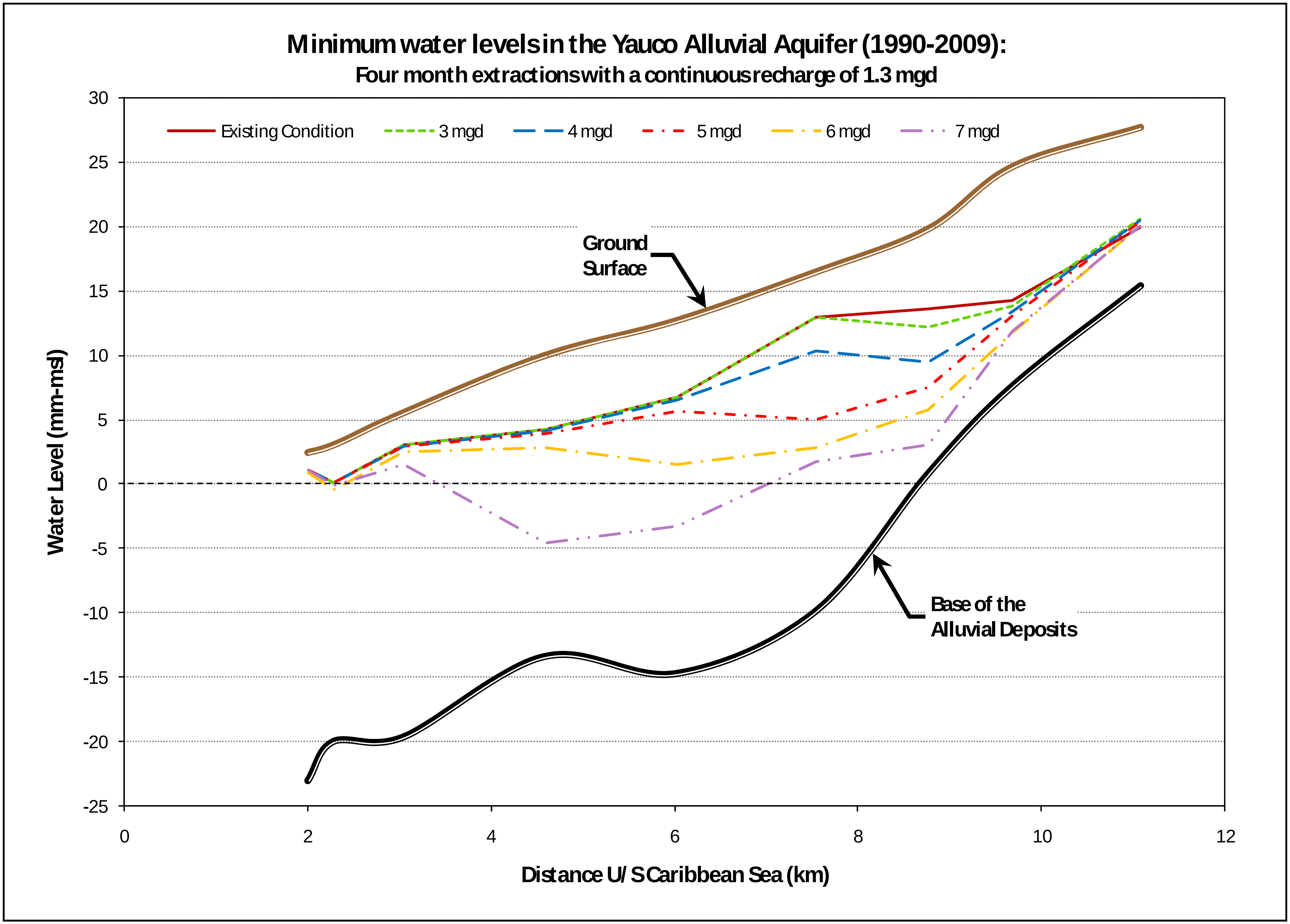

Figure 26: Conjunctive Use Model simulated minimum water profile at the Yauco Alluvial Aquifer for a continuous extraction from May to August and with a constant recharge of 1.3 mgd.

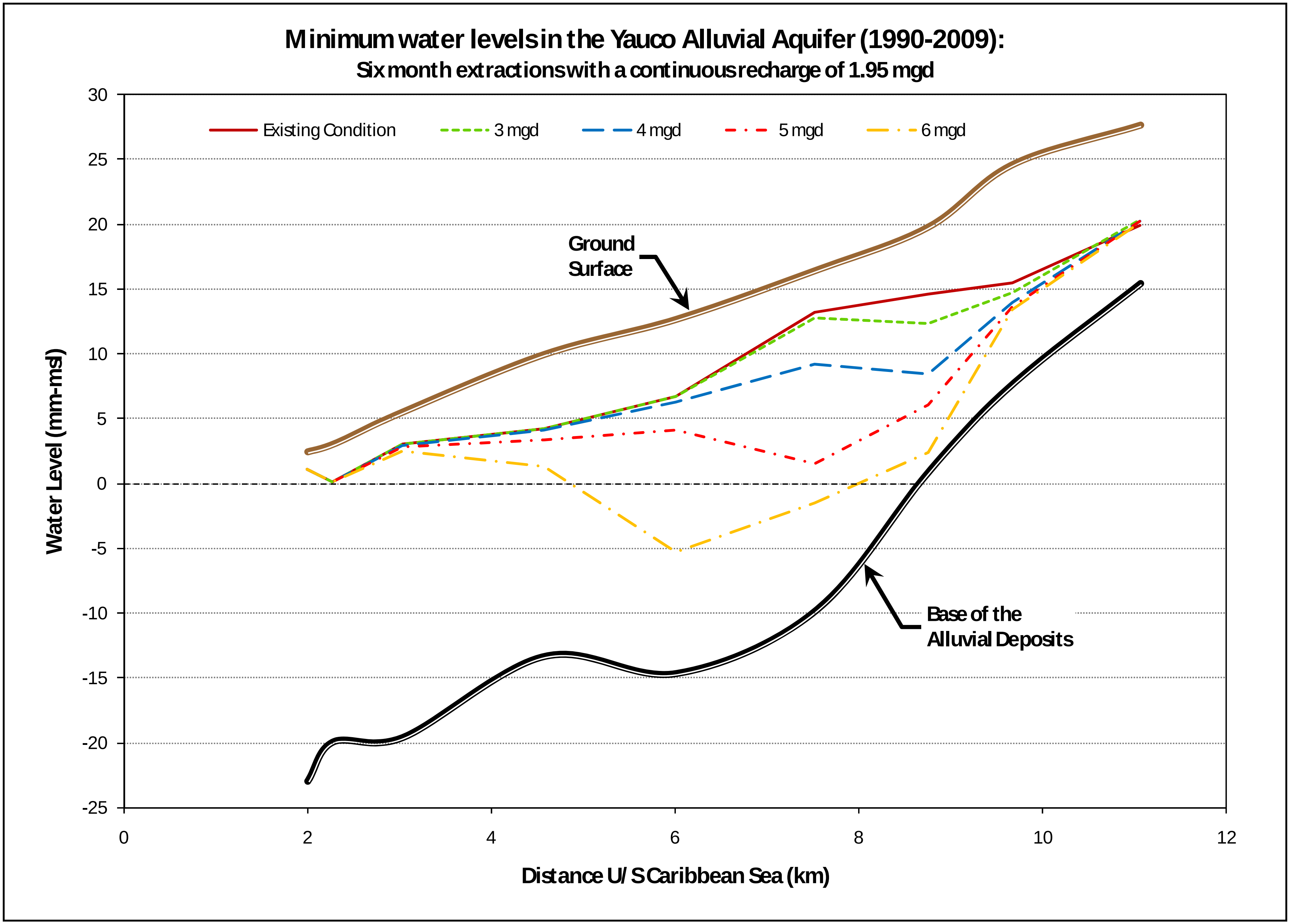

Figure 27: Conjunctive Use Model simulated minimum water profile at the Yauco Alluvial Aquifer for a continuous extraction from March to August and with a constant recharge of 1.95 mgd.