DEVELOPMENT OF A REGIONAL INTEGRATED HYDROLOGIC MODEL FOR A TROPICAL WATERSHED

by

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ABSTRACT

A preliminary hydrologic regional conceptual model was developed for a coastal tropical basin and implemented in an integrated, fully distributed, physically based, numerical model. The model attempts to include features of both the surface and subsurface hydrologic systems. During the development of the model, a geographic information system was developed to storage, manage, and process geographic information; and to produce the inputs required by the numerical model. Some preliminary runs were performed to check the response of the model to variation of some parameter values, in terms of the aggregated total annual discharge of two rivers at flow gauging stations, and the ground-water head at some locations within the study area. Limitations and assumptions of the conceptual model were stated; and recommendations for its future refinement and calibration are presented.

RESUMEN

El objetivo principal de esta investigación fue desarrollar un modelo hidrológico conceptual preliminar a escala regional que tuviera en cuenta características de los sistemas de agua superficial y subterránea para una cuenca costera tropical; e implementarlo en un modelo numérico distribuido físicamente basado. Un sistema de información geográfica fue desarrollado para almacenar y procesar la información espacial y generar la información requerida por el modelo numérico. Se llevaron a cabo algunas simulaciones preliminares con el modelo con el propósito de evaluar sus respuestas ante el cambio en el valor de algunos parámetros, en términos del caudal total anual combinado de los dos principales ríos que drenan el área en sitios de estaciones de aforo; y los niveles potenciométricos de agua subterránea para algunos sitios dentro del área de estudio. La investigación describe las limitaciones del modelo y da recomendaciones para su refinamiento y calibración en futuros estudios.

ACKNOWLEDGEMENTS

I would like to thank the NASA-EPSCoR's Program of the University of Puerto Rico-Mayagüez Campus for providing financial support for this research. Also, I would like to thank all the agencies and people who made possible the development of this model, especially:

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1 INTRODUCTION

Diverse water resource related problems are reported everyday worldwide, and their solutions frequently become critical in counties of the humid tropics, where dense populations often exist. In the Caribbean region, one of the islands which experiences various types of water resource problems is Puerto Rico; including pollution of water bodies (e.g. rivers and aquifers), flooding, adequate public water supply, sedimentation of reservoirs, saltwater intrusion, and degradation of coastal waters.

Numerical hydrologic models have become important tools to analyze water resource problems, and can aid in the selection of alternative solutions and/or preventive measures. One of the first aspects to be considered in a hydrologic modeling study is the development of the system conceptual model. Translating the physical system into a conceptual model that can be numerically simulated is perhaps the most important step in the hydrologic modeling process.

Some hydrologic models include the simulation of one or two hydrologic processes (e.g., overland flow and river channel flow, unsaturated flow and evapotranspiration, or ground-water flow). A hydrologic modeling effort which intends to simulate the main surface and subsurface water flow processes in a coupled way through a numerical engine becomes a challenging and interesting topic of research nowadays. This kind of model could improve our understanding of the interrelations among different processes of the land phase of the hydrologic cycle, and give a broader picture of the entire system to be modeled.

1.1 OBJECTIVE

The objective of this study is to develop a preliminary regional conceptual model of a tropical coastal watershed (819.10 km^2) and implement it in an integrated, fully distributed, physically based, numerical model. Integrated hydrologic modeling is understood in this study as an effort to simulate surface water and ground-water hydrologic processes in a coupled way.

The calibration and validation of this model is beyond the scope of this research and it is proposed for future studies.

This research is part of a much wider scope project being developed by the Caribbean Climate Studies Group (CCG) at the University of Puerto Rico at Mayagüez (UPRM). Researchers in this group are interested in evaluating climate change impacts in the annual water balance of a tropical watershed at a regional scale. The conceptual model of this study and its implementation in a numerical hydrologic model will become a first preliminary step to evaluate alternatives to perform gross estimations of the annual water budget at a regional scale. This study shows the potentiality of an integrated hydrologic model to produce water budget estimates.

The development of the conceptual model described in this research was based mainly on the review of available previous studies, reported hydrologic data, and GIS maps. Much of the data for the study area is limited in terms of availability, temporal consistency, and existence. These factors constitute one of the main limitations of the conceptual model, which has to be understood just as a first preliminary attempt to develop a regional scale integrated hydrologic conceptual model of an area, which presents great diverse of physical and hydrologic features (e.g. topography, land cover, soils type, hydrogeologic characteristics, etc). Therefore, this model is intended to be improved during future decades as more data become available, or an improved understanding of the hydrology of the region evolves. It is not the objective of this study to implement a model which might be used for planning or for the design of hydraulic structures purposes within the study area.

2 PREVIOUS PUBLICATIONS

Integrated hydrologic modeling implies the development of conceptual models which include the surface water and the ground-water systems, and its implementation in numerical models. In this chapter some integrated hydrologic modeling efforts, as well as, some numerical models which are capable of accounting for most of the main processes of the land phase of the hydrologic cycle are presented. First, some integrated hydrologic modeling efforts developed in different places are presented.

Hawaii (US)

An implementation of the integrated (surface water and ground-water) hydrologic numeric model Mike She (DHI, 2005) coupled with Mike 11 (DHI, 2004a, 2004b) was performed to predict stream flow of a flashy-flood-producing mountainous stream at 15-min intervals in Hawaii (Sahoo et al., 2006). The study area is the Manoa-Palolo watershed (24.60 km^2) located in the island of Oahu. Elevation of the land surface varies from 3 to 909 m above mean sea level. Land use of the watershed includes conservation lands, small scale agricultural lands, and high-density urban lands. The geology of the area includes basalts, sediments and coastal plain deposits consisting of marine and terrestrial sediments, limestone, and reef deposits (Sahoo et al., 2006).

For the implementation of the model in Mike She, the conceptual model included topographic, land use, soil type, and geologic information. Topographic information had a spatial resolution of 30 m x 30 m and was obtained from the soil survey Geographic (SSURGO) database of the National Resources Conservation Service (NRCS) (Sahoo et al., 2006). Thirty one (31) soils types were identified for the area, based on SSURGO classification. These soils were reclassified into 16 categories by grouping similar soils with different slopes (Sahoo et al., 2006). ArcGIS tools were used to deal with spatial data. Seven land use categories were conceptualized for the study area. Values of leaf area index for different land use categories were modified from reported literature values as deemed appropriate for the study area conditions, due to the unavailability of measured data. Initial values for horizontal and vertical hydraulic conductivity of the saturated zone were assumed taking into account reported literature values, and were changed during the calibration stage . A single value of hydraulic conductivity was used for the entire watershed, given the unavailability of detailed spatially distributed data (Sahoo et al., 2006). Collected 15 minute rainfall data from two rain gauge stations located in the study area were used for the simulation. Reference evapotranspiration (ET_o) was computed with weather data collected at a station close to the watershed, using the Penman Monteith method implemented within the computer software REF-ET (Allen, 2002; cited by Sahoo et al., 2006). The ET_o was assumed to be constant over the entire watershed, given the absence of other reference stations to do an aerial interpolation. Values of the crop coefficient (K_c) were assumed from literature reported values to compute evapotranspiration ($ET_c = ET_o * K_c$) for specific types of vegetation. Initial values for the Kristensen and Jensen ET parameters C1, C2, C3, C_{int}, and A_{root} were assumed as recommended by the Mike She manual. Initial values for Drainage depth (D_D) and drainage time (D_T) used in the drainage sub-model, were established in the range of typical values. Manning's number was assumed to be constant for all channels (Sahoo et al., 2006).

Given the high computer time requirements of the integrated model to simulate the entire watershed, a detailed calibration was first applied to a sub watershed inside the study area to examine the effects of parameters on stream flow estimation, and that information was then applied for the calibration of the complete area (Sahoo et al., 2006). To measure the efficiencies of the Mike She prediction performance the statistical criteria used were the root mean square error (RMSE), correlation coefficient (R), and mean error (ME). Due to the lack of reliable field data, the simulated ground-water table could not be compared with real values (Sahoo et al., 2006, p.101). It was found that, for this study, the distribution of rainfall over the watershed is important in stream flow estimation, and that the shape of the hydrograph is sensitive to changes in the Manning's number and hydraulic conductivities. Given that the spatial resolution of the input topographic data could not account for roads, small buildings and other impervious surfaces, it was noted that digital surface elevations maps at a finer scale could improve the results (Sahoo et al., 2006). The authors of the study consider that this model has a potential use with future refinements in input data, and let know that this was their first attempt to use a distributed model like Mike She in a mountainous tropical watershed (Sahoo et al., 2006).

Idaho (US)

Said et al. (2005) used an integrated hydrologic surface and ground-water model to estimate the annual total water budget in the Big Lost River Basin in Idaho. The Big Lost River Basin drains an area of about 3,730 km^2 and is a major tributary to the Snake River Plain aquifer. The model used for this study was FHM which has two public domain components: Hydrological Simulation Program – FORTRAN (HSPF) and Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (MODFLOW). The ground-water domain grid was discretized into 35 rows and 50 columns with a uniform cell size of 867 m in each direction. Ground-water and streamflow calibration were performed for the model. For the ground-water, a comparison between observed and simulated ground-water levels was done. The major parameters adjusted were the transmissivity and the storage coefficient. Daily stream flow data (downloaded from the USGS online database) for two sub-basins were used for the stream flow calibration. The results of the study allowed identification of some sub-basins with more ground-water development potential than others (Said et al., 2005). The authors of the study believe the model can help predict ground-water elevations efficiently and estimate the components of the water budget.

Emely Marshes (England)

A modeling study applying the Mike She hydrological model coupled with the Mike 11 hydraulic model is described by Thompson et al. (2004). The model was developed for an approximate area of 8.7 km^2 in the Emely Marshes (southeast England). According to Thompson et al. (2004), the marshes are characterized by a complex ditch network and a number of control structures. Also, the wetlands are subject to periodic inundation during autumn and winter. The model used a 9,271 grid squares of 30 x 30 m and was intended to represent the hydrological conditions during a period of 36 months for which there were available sufficient data for calibration and validation purposes (Thompson et al., 2004). The calibration parameters used for the Mike She model were: the saturated hydraulic conductivity, Manning's n number for overland flow, drainage time constant, bypass flow ratio, and soil moisture threshold. Manning's coefficient for channel flow and leakage coefficient were the parameters to be calibrated for the Mike 11 model. Ground-water depth (obtained from piezometer observations) and ditch water surface elevations at different locations were the calibration and validation targets. The period for calibration was from June 25, 1997 to December 31, 1998; and for validation the following 18 month period was used. In general, the results obtained reproduced the highly seasonal nature of both ground-water and ditch water level, and demonstrated the close relationship between flooding, and ground-water and ditch water levels Thompson et al. (2004).

<u>Sjaelland Island (Denmark)</u>

Henriksen et al. (2003) describes an integrated modeling study for the Sjaelland Island (7,330 km^2) in Denmark. The hydrological processes modeled included snow accumulation and melt, overland flow, unsaturated zone processes, ground-water flow and river flow. The model code used to simulate the ground-water flow system was Mike She (Henriksen et al., 2003). The horizontal grid size chosen was 1 x 1 km^2. The calibration and validation targets were ground-water heads and daily stream flow data. Ground-water head data from 4,439 wells and daily stream flow from 28 river gauging stations were used for the calibration and validation procedure. During the construction of the model a guiding principle was to have as few free parameters as possible, therefore, uniform parameter values throughout the study area were used for geological layers and most of the overland parameters (Henriksen et al., 2003).

A sensitivity analysis showed that the most sensitive parameters were the hydraulic conductivity for some materials, specific yield, drainage time constant, and aquifer-river bottom leakage coefficient. A set of four numerical criteria were selected to evaluate the model performance taking into account the deviation between simulated and observed ground-water heads; and the ability to simulate: average runoff, variation in the discharge hydrographs and low flow conditions for a particular river gauging station. Based on the final results, the authors of the study concluded that the model was capable of simulating reliable hydraulic heads and discharges, and can be used for assessing ground-water recharge and impacts of ground-water development scenarios on a regional scale, investigating the impact of climate changes on water resources availability, and can serve as a water flow model for assessing nitrogen fluxes at a catchment and regional scale (Henriksen et al., 2003). Likewise, they clarify that due to the coarse scale of the model, there are limitations in predicting the behavior at a local scale.

The next section presents a brief description of four of the hydrologic model codes identified to be capable of simulating the main processes in the land phase of the hydrological cycle, which were specifically considered for its use in this study. The numerical model used in this study (i.e., Mike She / Mike 11) is also included.

WASH123D

WASH123D is a numerical model capable of simulating flow, reactive chemical and sediment transport in a watershed. The watershed is conceptualized as a system composed of 1-dimensional channel networks, 2-dimensional overland, and 3-dimensional subsurface sub domains (Yeh et al., 1998). The model describes the 1-dimensional channel flow and 2-dimensional overland flow with the Saint Venant equations (Cheng and Hunter, 2004). The 3-dimensional variably saturated subsurface flow is described by Richard's equation (Yeh et al., 1998). This model was developed by Professor George Yeh (University of Central Florida) and his colleagues (Edris, 2003). The subsurface flow part of the model is based on the well-known computer model FEMWATER. Although FEMWATER simulates variable density flow, Version 1 of WASH123D does not (Yeh et al., 1998). The model code can run in the Ground-water Modeling System (GMS) (Sheer, 2000) which allows the model to have a Graphical User Interface (GUI) for pre and post processing with Geographic Information System (GIS) capabilities. At October 2005, the interrelation between the GMS and the serial version of WASH123D was being developed and improved. For comprehensive watershed management plans, the USEPA and the U.S. Army Corps of Engineers (USACE) endorses WASH123D (US Army Corps of Engineers et al., 2002). Simulation run times for WASH123D can be very long (Sheer, 2000; SFWMD, 2001). At October 2005, a parallel version of WASH123D was being developed by the Engineer Research and Development Center (ERDC) of the USACE.

IHM

The Integrated Hydrologic Model (IHM) coupled the ground-water model MODFLOW and the surface water model Hydrological Simulation Program – FORTRAN (HSPF). According to Ross et al., (2004), the IHM model had its origins in the FHM model which was sponsored initially by the Florida Institute of Phosphate Research (FIPR) and later by the Southwest Florida Water Management District (SWFWMD). An adaptation of this model was developed by SDI Environmental of Tampa and was called Integrated Surface and Ground-water (ISGW), which has been used in Tampa Bay Water projects (Ross et al., 2004). The development of IHM is the product of a revision of ISGW model and its application to the northern Tampa Bay area project funded by Tampa Bay Water and SWFWMD (Ross et al., 2004).

The model components explicitly account for the main processes in the land face of the hydrological cycle including: interception, evapotranspiration, runoff, recharge, stream flow, and ground-water flow. The outputs of the model include surface water and ground-water flows to wetlands, streams and lakes, evapotranspiration from all storages, reach stage, soil moisture, recharge to the ground-water systems and storage, heads and fluxes in the ground-water system (Ross et al., 2004). The surface water component of the model, HSPF, can simulate non point source pollutant loadings for a watershed and performs flow and water quality routing in reaches (US Army Corps of Engineers et al., 2002). It uses irregularly shaped watershed sub-basins that are discretized into multiple land segments with pervious and impervious land parcels. IHM allows for multiple land segment types (based on land use, soil type, surface slope, and other surface and subsurface characteristics) to discretize land-based hydrologic processes within each sub-basin (Ross et al., 2004). The ground-water flow is simulated in three dimensions by MODFLOW using a finite difference approach. The unsaturated zone is simulated by IHM using an idealized moisture content profile (Ross et al., 2004).

Given the extensive spatial data requirements of the model, it is impracticable for all but the simplest of model conceptualizations to run IHM without GIS applications. The database used by the model has the capability to import data from many GIS applications (Ross et al., 2004). The use of pre and post processors for HSPF (i.e. GenScn, WinHSPF, WDMUtil) and MODFLOW (i.e. Ground-water-Vistas) is not required but recommended (Ross et al., 2004). Although the code of IHM will be public domain, the model was not yet available for the public at February 2005 (personal communication, Patrick Tara, February of 2005). The component models, MODFLOW and HSPF, are public domain codes. IHM has been used to simulate the integrated hydrologic system in an area in West Central Florida resulting in the Integrated Northern Tampa Bay (INTB) model (Aly and Tara, 2004). IHM is Windows-based and was designed to run on personal computers (PCs). In its present state, the model cannot run on a supercomputer (personal communication, Patrick Tara, February 2005).

MIKE SHE / MIKE 11

MIKE SHE (DHI, 2005) / MIKE 11 (DHI, 2004a, 2004b, and 2005) is a deterministic, physically-based, spatially-distributed, finite difference, integrated surface water and ground-water model (US Army Corps of Engineers et al., 2002). MIKE SHE coupled with MIKE 11 is capable of modeling the main processes in the land phase of the hydrological cycle including: interception, evapotranspiration, 1-dimensional open channel flow, 2-dimensional overland flow, 1-dimensional unsaturated soil flow, and 3-dimensional ground-water flow. Mike She does not include variable density flow (Written communication, Douglas Graham, November 2005). There are different time steps for each one of the components of the hydrological system which are solved by separate modules.

For the ground-water flow MIKE SHE solves the 3-D fully saturated flow equation. In the unsaturated zone there are three options for calculating vertical flow; one of them being the 1-D Richard's equation. The diffusive wave approximation of the Saint Venant equations can be solved in 2-D for overland flow. For 1-D open channel, the flow formulation of MIKE 11 is based on the fully dynamic wave equation. The transport of chemicals can also be simulated in both surface and ground-water, and the model is capable of simulating agriculture irrigation as well (SFWMD, 2001).

The model has a graphic user interface (GUI) with pre- and post-processing capabilities. Input spatial data can be read in GIS format, and spatial output can be saved in GIS format (shape files). MIKE SHE is based on the European Hydrological System that was developed in a joint effort by the Institute of Hydrology (United Kingdom), SOGREAH (France), and the Danish Hydraulic Institute (US Army Corps of Engineers et al., 2002). MIKE SHE / MIKE 11 are propriety software available directly from DHI Water and Environment. The current version of the model cannot run on a supercomputer. MIKE SHE has been adapted in a number of projects that involve ground-water surface-water interaction in Florida (SFWMD, 2001). Applications of Mike She has been reported in the fields of flood forecasting, characterization of soil hydraulic properties, assessment of ground-water contamination, irrigation planning and management, and surface and ground-water hydrology (Sahoo et al., 2006).

GSSHA

GSSHA, Gridded Surface Subsurface Hydrologic Analysis is a multi-Dimensional, physically-based, finite difference, hydrologic model. GSSHA is a reformulation and enhancement of the CASC2D model originally developed by Prof. P. Y. Julien at Colorado State University (Downer and Ogden, 2002a). The Watershed Modeling System (WMS) is used as the graphical user interface (GUI) for pre and post processing and has capabilities to read information in GIS format. The hydrologic processes that can be simulated with the model code and the approximation techniques are: precipitation distribution (Thiessen polygons, inverse distance-square weighting), snowfall accumulation and melting (energy balance), precipitation interception (empirical two parameter), overland water retention (specified depth), infiltration (Green and Ampt, multilayered Green and Ampt, Green and Ampt with redistribution and Richard's equation), overland flow routing (two dimensional diffusive wave), channel routing (one dimensional diffusive wave), evapotranspiration (Deardorff, Penman-Monteith with seasonal canopy resistance), soil moisture in the vadose zone (Bucket model, Richard's equation), lateral ground-water flow (two dimensional vertically averaged), stream/ground-water interaction (Darcy's law) and exfiltration (Darcy's law) (Downer and Ogden, 2002a). The model code has been used in USACE (U.S. Army Corps of Engineers) projects for hydrologic modeling purposes (personal communication, Aaron Byrd (ERDC), September 2005).

The GSSHA code is continuously being improved and changes in the code and input/output requirements may be made by the authors at any time (Downer and Ogden, 2002a). In October 2005 there were intentions to parallelize the code (personal communication, Aaron Byrd (ERDC), September 2005).

3 METHODOLOGY

Some of the most important activities performed to achieve the objectives of the present study are briefly described below.

3.1 DATA GATHERING

The development of a conceptual model for an integrated, distributed, physically based model requires diverse information about the physical features of the study area and measured data of the hydrologic variables. To develop the conceptual model for the present study different data were collected in diverse formats and from different sources. The information included topography, soil types, land cover, river network, hydrogeologic data; as well as measured data, including flow rate and cross section data for the main rivers, ground-water levels, precipitation, and temperature data at climate stations.

The interaction with some agencies (e.g. U.S. Geological Survey (USGS), U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS), U.S. Army Corp of Engineers, Puerto Rico Electric Power Authority, Puerto Rico Water Resources and Environmental Research Institute), private companies (e.g. Nacer Pumps Installation Services, DHI) and researchers (e.g. Dr. Yeh at the University of Central Florida, Dr. Padilla at the University of Puerto Rico) to request information and to share knowledge was a very important aspect of this research. In particular, the frequent communications with different people at the U.S. Geological Survey office in San Juan was essential to accomplish this study.

3.2 DEVELOPMENT OF A GEOGRAPHIC INFORMATION SYSTEM (GIS)

A comprehensive GIS was developed in ArcGis 9.1 for the study area to accomplish the following purposes:

- Storage, manage, and process all geographic information. Large quantities of spatially distributed information and data were gathered during this research. Most of the information had to be processed using GIS capabilities and tools to develop the conceptual model.

- Produce the inputs required by the numerical model. The Graphical User Interface (GUI) of the numerical model used to implement the conceptual model has GIS capabilities which allow the user to input data in shape file format (*.shp).

The GIS development included information about: land elevation, soil types, land cover, distribution of the aquifers, ground-water wells location, climate stations locations, river network system, and river flow stations, among others.

3.3 CONCEPTUAL MODEL DEVELOPMENT

As a result of the review of available information and data, a preliminary regional conceptual model was developed for the study area, which attempts to include features of both the surface and subsurface hydrologic systems of the study basin. The purpose of this model was to translate the physical system into one that could be modeled in an integrated, physically-based, spatially-distributed, numeric hydrologic model. The conceptual model, once it is refined in future studies, will become a first preliminary step to evaluate alternatives to perform gross estimations of the annual water budget at a regional scale.

3.4 IMPLEMENTATION AND PRELIMINARY MODEL RUNS

The implementation stage is understood in this study as the setting up process of the conceptual model into the numerical model. This stage included the preparation of all geographic and hydrologic data to be input in the formats required by the GUI of the numerical model.

Some preliminary runs were performed to check the response of the model to variation of some parameter values; in terms of the aggregated total annual discharge of the main rivers at the flow gauging stations, and the ground-water head at some locations within the study area.

4 STUDY AREA DESCRIPTION

4.1 OVERVIEW

The study area is located in the western part of the main island of Puerto Rico, and corresponds with the Mayagüez Bay drainage basin (Figure 4.1.1). The area has an aerial extension of 819.10 km^2, and is characterized by a wide diversity of physical and hydrological features (e.g., geology, topography, climate, and land use). Although, the Mayagüez Bay drainage basin is considered one of the most valuable resources of the region, its water resources are affected by waste discharges and the expansion of urban development (PRWRERI, no date [n.d.]). This coastal basin is currently an interesting research area for some scientists at the University of Puerto Rico.

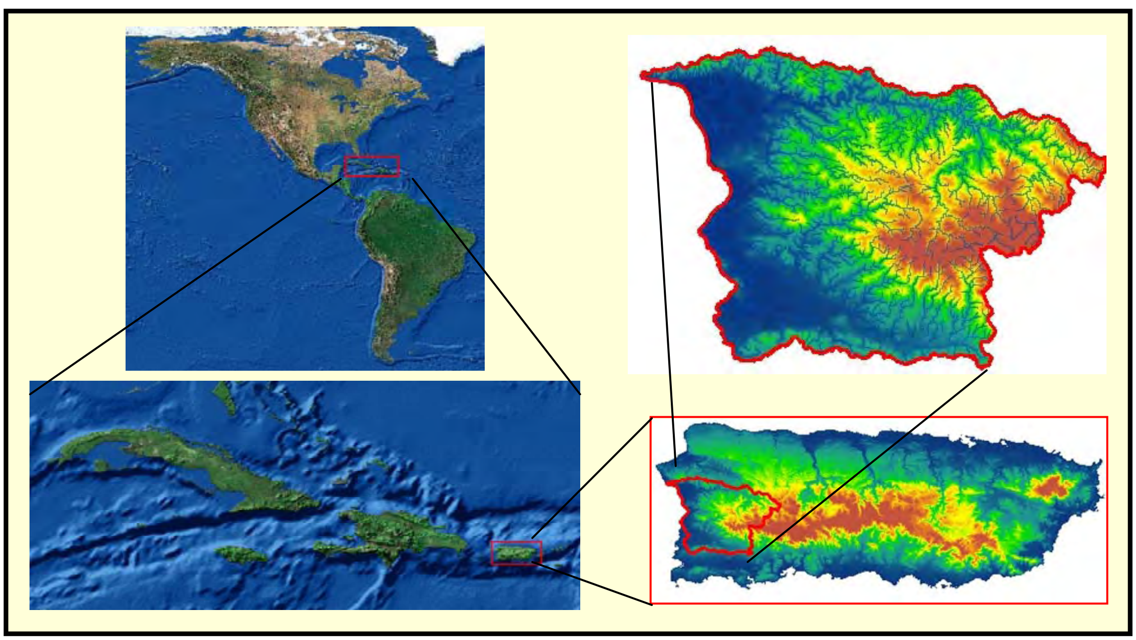


Figure 4.1.1. Location of the study area.

The three major rivers draining the area are: the Río Grande de Añasco, Río Guanajibo, and Río Yagüez, all of them flowing east to west to the Mona Passage which separates the Atlantic Ocean from the Caribbean Sea. Elevations in the study area vary from mean sea level in the western part of the study area along the coast to about 960 meters above mean sea level in the east part in the Río Grande de Añasco watershed (Figure 4.1.2).

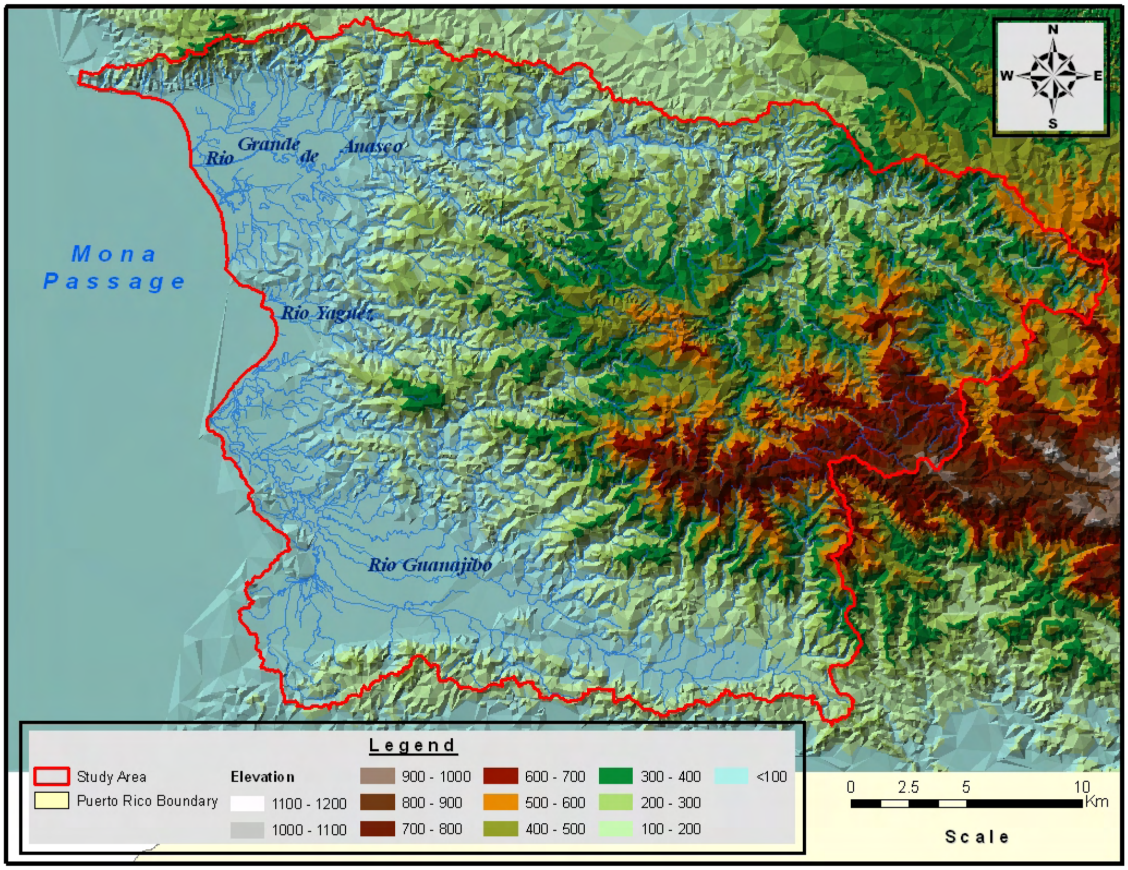


Figure 4.1.2. Triangulated surface (TIN) of the study area land elevation (units are meters over mean sea level).

The study area encompasses four municipalities (Añasco, Mayagüez, Las Marías, and Hormigueros), and parts of another seven municipalities (San Sebastián, Lares, Adjuntas, Maricao, Sábana Grande, San Germán, Cabo Rojo, and Rincón) (Figure 4.1.3). Table 4.1.1 presents the population for all these municipalities for 2000 year, according to Comisión Estatal de Elecciones de Puerto Rico (Comisión Estatal de Elecciones de Puerto Rico web site, n.d.). The municipality with the highest population is Mayagüez, which lies entirely within the study area.

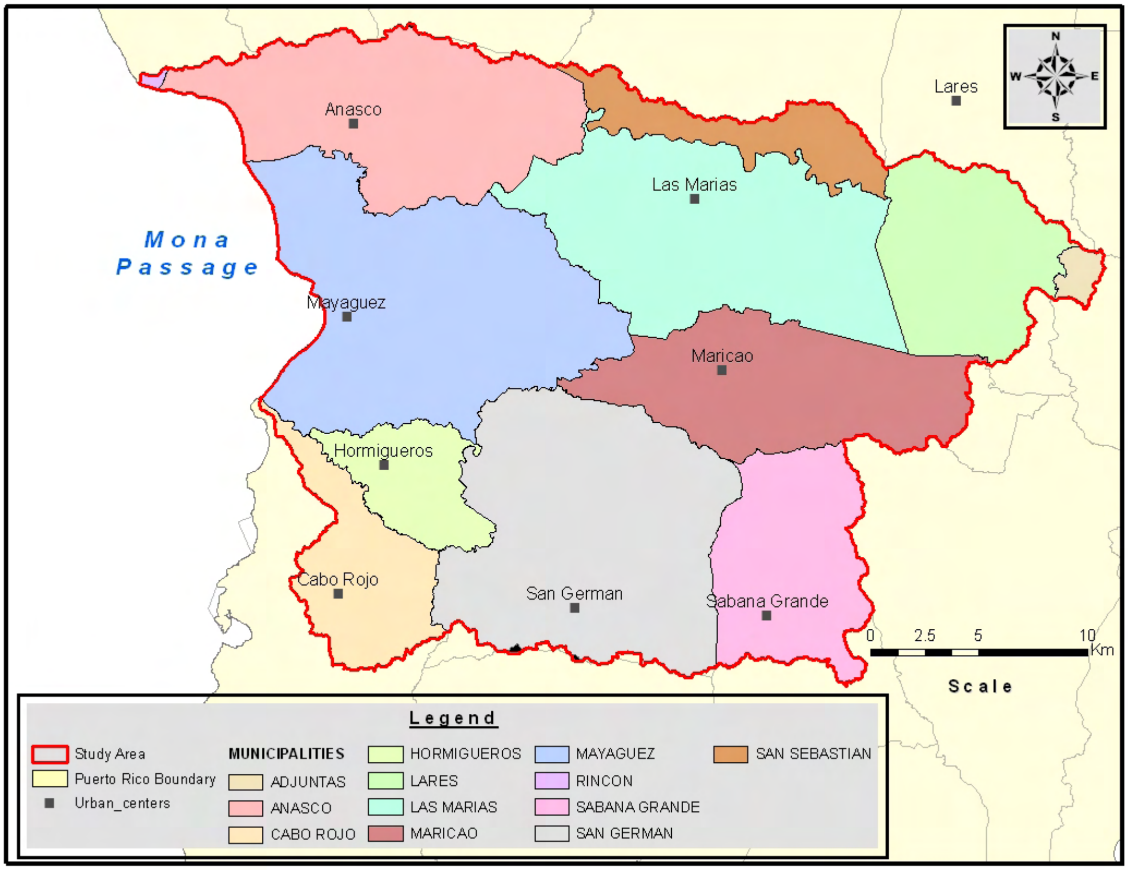


Figure 4.1.3. Municipalities and principal population centers.

Table 4.1.1. Population of some Puerto Rico municipalities according with Comisión Estatal de Elecciones de Puerto Rico (Comisión Estatal de Elecciones de Puerto Rico web site, n.d.).

Municipio	2000 Population
Mayagüez	98,434
Cabo Rojo	46,911
San Sebastián	44,204
San Germán	37,105
Lares	34,415
Añasco	28,348
Sabana Grande	25,935
Adjuntas	19,143
Hormigueros	16,614
Rincón	14,767
Las Marías	11,061
Maricao	6,449
Total =	**383,386**

Land use within the study area is mostly forest, agriculture, pasture, and urban development. The principal population centers within the study area are the towns of Mayagüez, Cabo Rojo, San Germán, Añasco, Sabana Grande, Hormigueros, Las Marías, and Maricao (Figure 4.1.3).

4.2 CLIMATE

Rainfall varies seasonally and geographically over the study area. National Climate Data Center (NCDC) climate normals 1971 – 2000 are shown in Figures 4.2.1, 4.2.2, and 4.2.3 and in Table 4.2.1, for three stations located within the study area (Figure 4.2.4). The data for these figures and table were obtained from the Southeast Regional Climate Center website (SRCC, n.d.). Average annual precipitation for those stations varies from 1,743.96 mm at Mayagüez City to 2,428.24 mm at Maricao station located at an approximate altitude of 863 m over mean sea level (NOAA, n.d.).

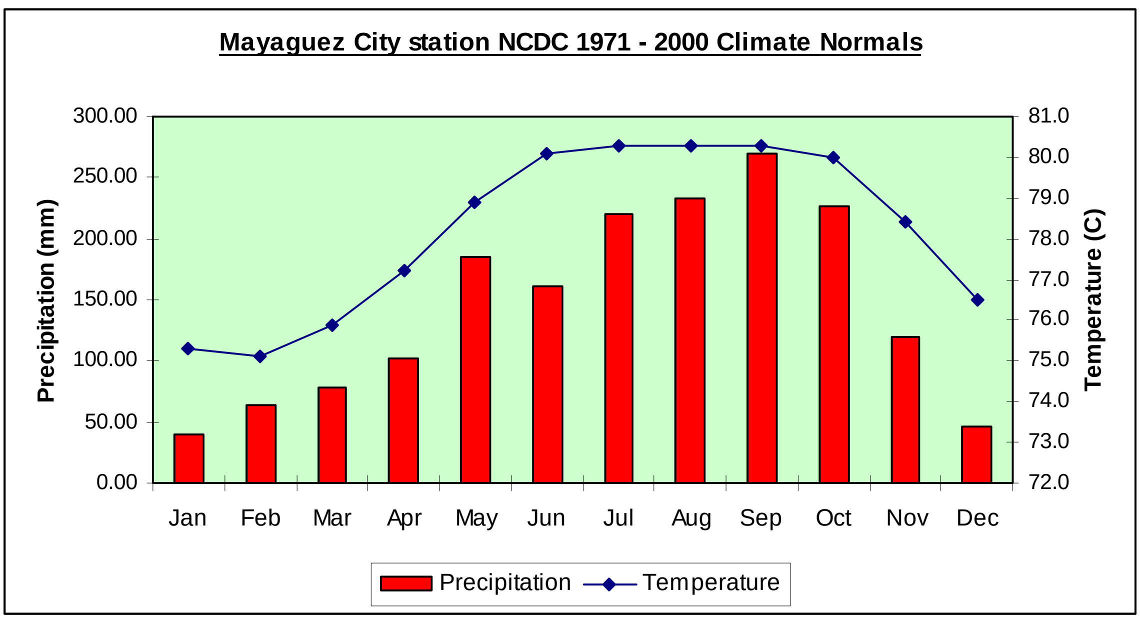


Figure 4.2.1. Mayagüez City station NCDC 1971 - 2000 Climate Normals. Location of the station is shown in Figure 4.2.4.

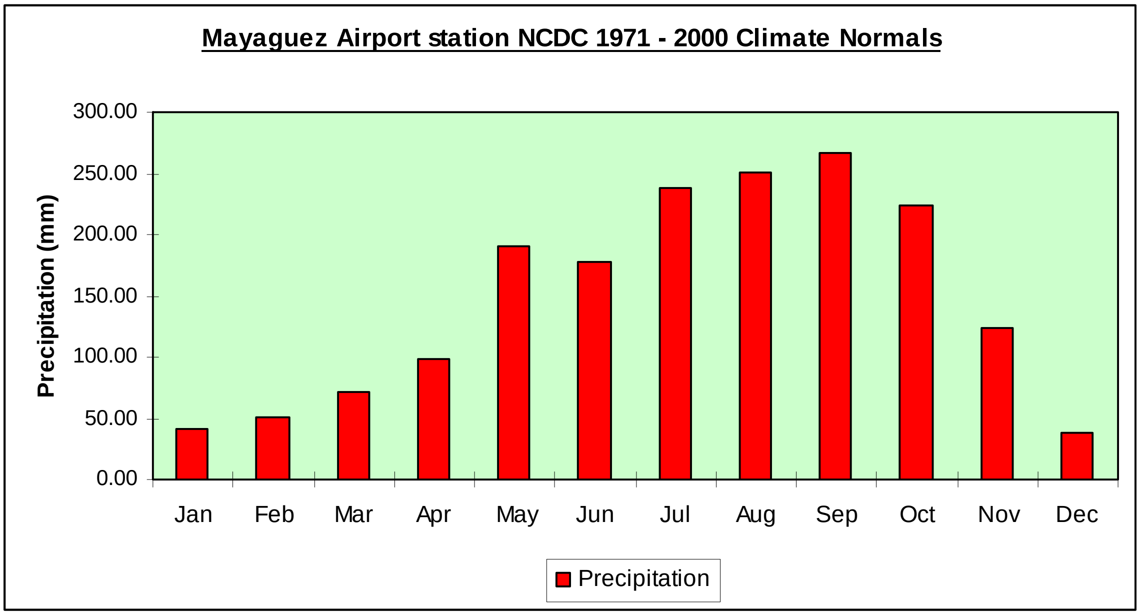


Figure 4.2.2. Mayagüez Airport station NCDC 1971 - 2000 Climate Normals. Location of the station is shown in Figure 4.2.4.

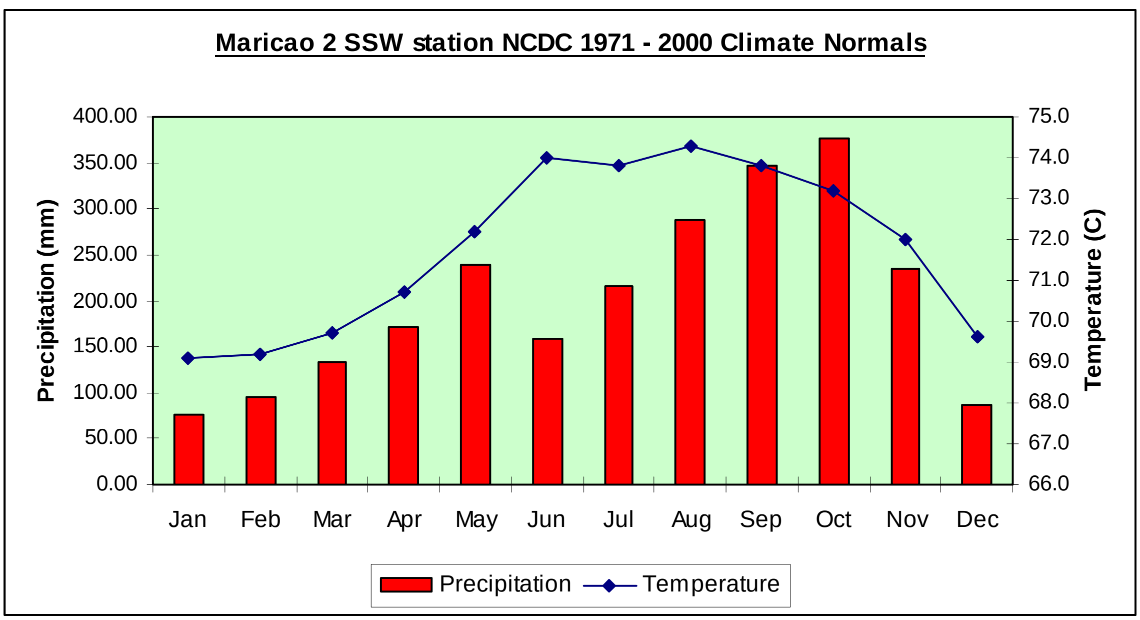


Figure 4.2.3. Maricao 2 SSW station NCDC 1971 - 2000 Climate Normals. Location of the station is shown in Figure 4.2.4.

Table 4.2.1. NCDC 1971 – 2000 Climate Normals.

Station				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mayaguez City	Temperature	Max	(ºF)	86.2	86.3	87.2	87.8	89.1	90.6	90.6	90.8	90.5	90.0	88.5	86.6	88.7
			(ºC)	30.1	30.2	30.7	31.0	31.7	32.6	32.6	32.7	32.5	32.2	31.4	30.3	31.5
		Mean	(ºF)	75.3	75.1	75.9	77.2	78.9	80.1	80.3	80.3	80.3	80.0	78.4	76.5	78.2
			(ºC)	24.1	23.9	24.4	25.1	26.1	26.7	26.8	26.8	26.8	26.7	25.8	24.7	25.7
		Min	(ºF)	64.3	63.9	64.6	66.5	68.6	69.6	70.0	69.8	70.1	69.9	68.3	66.3	67.7
			(ºC)	17.9	17.7	18.1	19.2	20.3	20.9	21.1	21.0	21.2	21.1	20.2	19.1	19.8
	Precipitation		(in)	1.59	2.52	3.05	4.04	7.26	6.32	8.68	9.16	10.61	8.93	4.70	1.80	68.66
			(mm)	40.39	64.01	77.47	102.62	184.40	160.53	220.47	232.66	269.49	226.82	119.38	45.72	1743.96
Mayaguez Airport	Precipitation		(in)	1.63	2.01	2.81	3.89	7.53	7.01	9.35	9.88	10.49	8.80	4.85	1.49	69.74
			(mm)	41.40	51.05	71.37	98.81	191.26	178.05	237.49	250.95	266.45	223.52	123.19	37.85	1771.40
Maricao 2 SSW	Temperature	Max	(ºF)	76.7	77.3	78.2	79.1	80.0	82.1	81.6	82.0	81.3	80.3	79.1	76.7	79.5
			(ºC)	24.8	25.2	25.7	26.2	26.7	27.8	27.6	27.8	27.4	26.8	26.2	24.8	26.4
		Mean	(ºF)	69.1	69.2	69.7	70.7	72.2	74.0	73.8	74.3	73.8	73.2	72.0	69.6	71.8
			(ºC)	20.6	20.7	20.9	21.5	22.3	23.3	23.2	23.5	23.2	22.9	22.2	20.9	22.1
		Min	(ºF)	61.5	61.1	61.1	62.2	64.3	65.8	66.0	66.6	66.2	66.0	64.8	62.5	64.0
			(ºC)	16.4	16.2	16.2	16.8	17.9	18.8	18.9	19.2	19.0	18.9	18.2	16.9	17.8
	Precipitation		(in)	3.01	3.75	5.28	6.79	9.43	6.28	8.52	11.32	13.66	14.86	9.29	3.41	95.60
			(mm)	76.45	95.25	134.11	172.47	239.52	159.51	216.41	287.53	346.96	377.44	235.97	86.61	2428.24

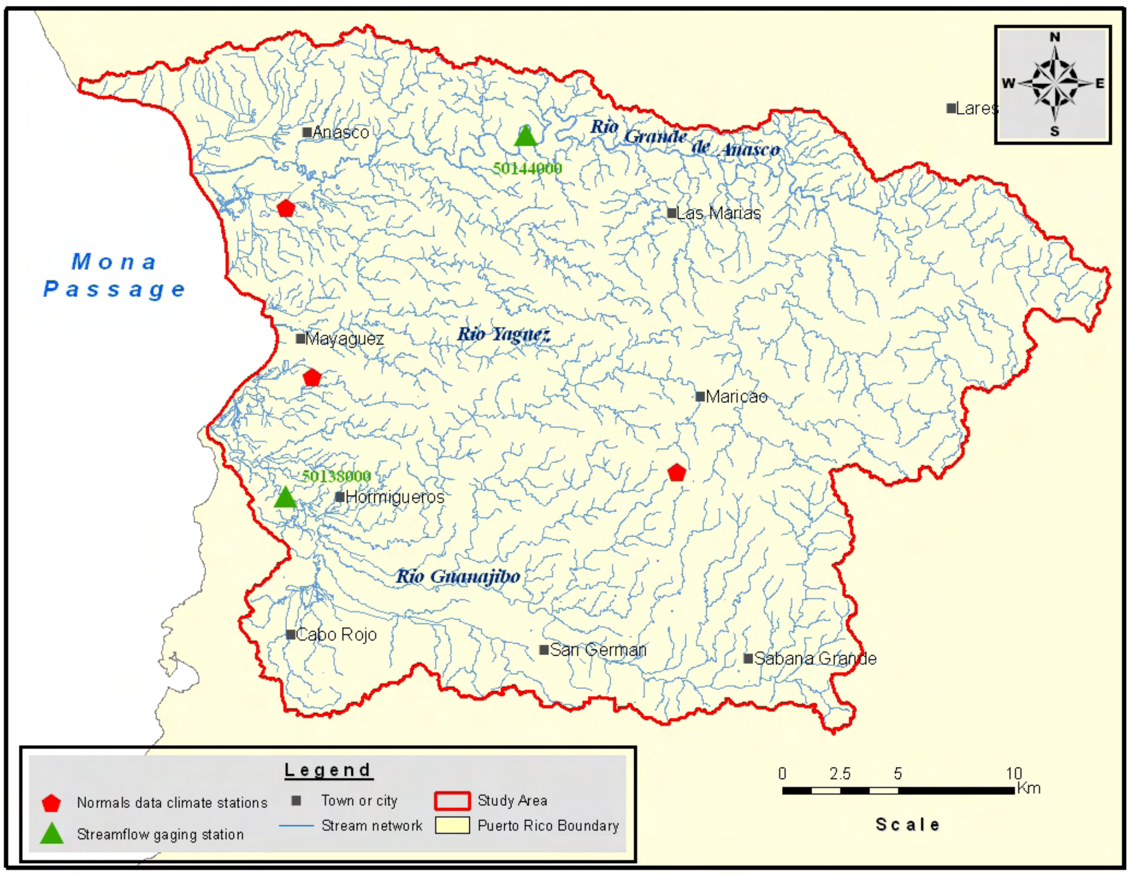
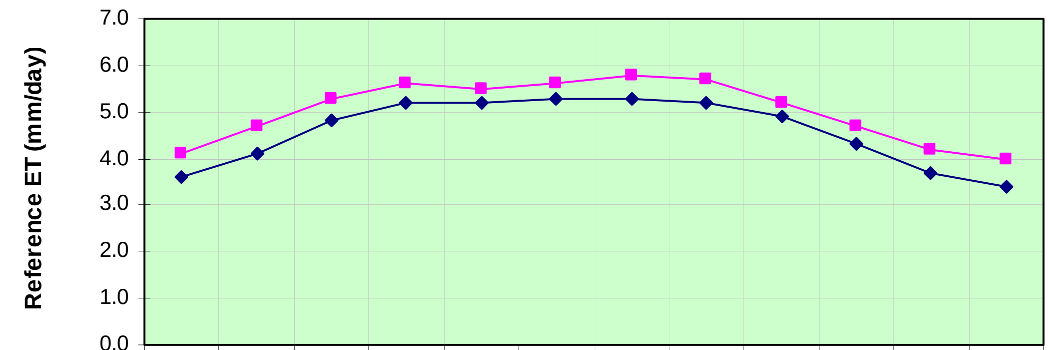


Figure 4.2.4. Streamflow gauging stations and normals data climate stations locations.

The wettest months are September and October, with a maximum value of 377.44 mm in October at Maricao 2SSW station; and the driest months are December and January, presenting a minimum value of 37.85 mm at Mayagüez Airport (December). A general pattern is presented at all stations: the rainy season occurs from early August to late October, with significant precipitation occurring during May; the driest period occurs from December to March.

Climate normals for temperature were available for two stations: Mayagüez City and Maricao 2SSW. Annual average temperatures range from 25.7 ºC at Mayagüez City to 22.1 ºC at Maricao 2SSW station. Average monthly temperatures over the year are higher at Mayagüez City than at Maricao 2SSW station, with the warmest months being July, August, and September with an average monthly mean value of 26.8 ºC at Mayagüez City station. The minimum monthly average temperature is presented in January with a value of 20.6 ºC at Maricao 2SSW station.

Direct measurements of actual evapotranspiration (ET_{actual}) were not available for the study area during the development of this study. Long-term average daily reference evapotranspiration (ET_o) was estimated using the Penman-Monteith equation for locations at Mayagüez and San Germán by Harmsen et al. (2002), and are presented in Figure 4.2.5. According with this data, mean monthly long term average daily ET_o ranges between 3.4 and 5.3 mm/day at Mayagüez; and from 4.0 to 5.8 mm/day at San Germán. Mean monthly long term average daily ET_o is higher for San Germán than Mayagüez station. For both locations the month with minimum mean monthly long term average daily ET_o is December, and the period with the highest values is from April to August. Minimum value of mean monthly long term average daily ET_o is presented at Mayagüez (3.4 mm/day), and the highest value is 5.8 mm/day at San Germán.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
San German	4.1	4.7	5.3	5.6	5.5	5.6	5.8	5.7	5.2	4.7	4.2	4.0
Mayaguez	3.6	4.1	4.8	5.2	5.2	5.3	5.3	5.2	4.9	4.3	3.7	3.4

Figure 4.2.5. Long-term average daily reference evapotranspiration estimated by Penman-Monteith Method (Harmsen et al., 2002). Locations are shown in Figure 4.2.4.

4.3 RIVER FLOW

The Río Grande de Añasco river (hereafter referred to as the Añasco river), originates at the junction of the Río Blanco and Río Prieto, southwest of Lares town. (Figure 4.3.1). The main tributaries of the Añasco River in the lower valley are Río Cañas, Río Casey, and Río Daguey. The upper reaches of the Añasco watershed contain four reservoirs: Lago Yahuecas, Lago Guayo, Lago Prieto, and Lago Toro, which are interconnected (Figure 4.3.1). These reservoirs are part of the Southwestern Puerto Rico Project, operated by the Puerto Rico Electric Power Authority (PREPA), and developed for hydroelectric power generation and irrigation of the lands in the Lajas Valley. Water from Yahuecas dam is diverted to the Lago Guayo through a diversion tunnel (Figure 4.3.1). From Guayo dam it is diverted southward through a tunnel to the Río Yauco watershed, picking up on their way, water from Prieto Dam which also receives some water from Toro dam (National Dam Safety Program, 1980a; 1980b; 1980c; Soler, 1999). There are no direct measurements data of the diversion flows through each one those tunnels by PREPA (personal communication, Pablo Roman (PREPA), July 05, 2005). For a more detailed description of the Southwestern Puerto Rico Project the reader is referred to the references:

National Dam Safety Program (1980a; 1980b; 1980c); Soler (1998; 1999); and Soler et al. (1999).

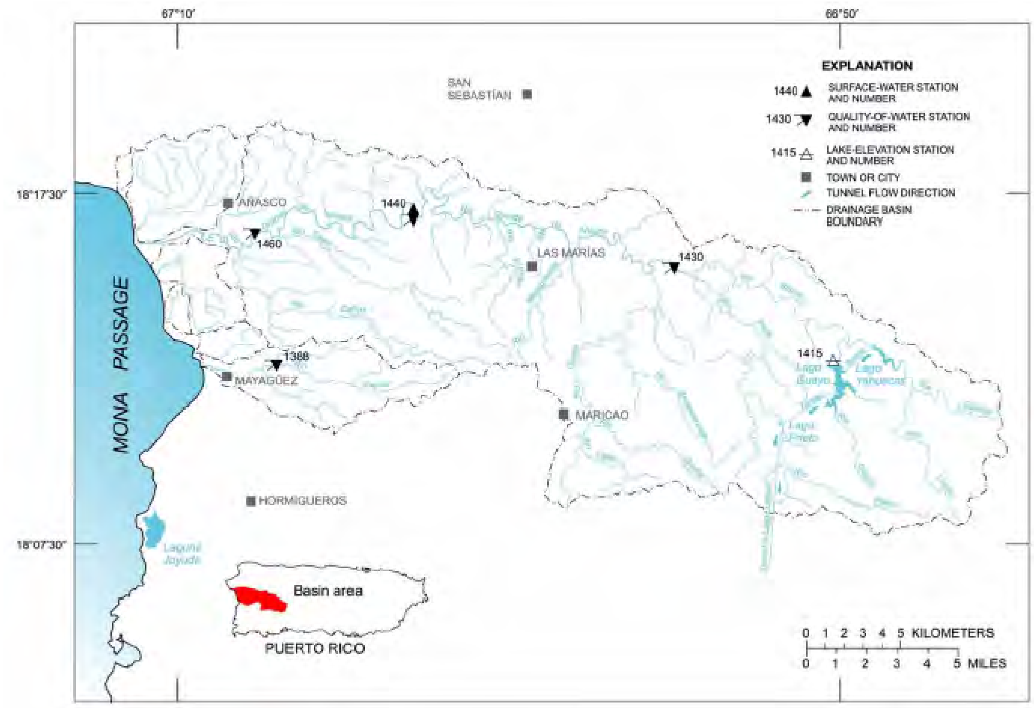


Figure 4.3.1. Río Grande de Añasco and Río Yagüez watersheds (Source: Figueroa et al., 2006; presented with authorization from the USGS Caribbean Water Science Center).

For the drainage area of the surface water station *50144000 Rio Grande De Añasco Near San Sebastian, PR* (Figure 4.3.1), the USGS does not include the areas above Lago Guayo, Lago Yahuecas, and Lago Prieto dams, and the area above Rio Toro diversion dam (Figueroa et al., 2006, p.431; personal communication, Pedro Díaz (USGS), February 02, 2007). According with Figueroa et al. (2006) the area above Lago Guayo, Lago Yahuecas, and Lago Prieto dams contributes only during high floods and the area above Rio Toro diversion dam contributes only part of its storm runoff to the drainage area of the station. For the purpose of the present study it was assumed that the contribution of water from the Lago Guayo, Lago Yahuecas, and Lago Prieto sub watersheds to the Añasco watershed downstream of them is not significant (for a regional water budget estimation), and therefore, those watersheds were not included as part of the Añasco draining watershed. Also, due to the non-availability of data about the contribution of the area above Río Toro diversion dam, the small area (9.1 km^2) was included as part of the Mayagüez Bay drainage basin. These assumptions need to be verified in future investigations, and constitute one of the limitations of the model developed in this study.

The Río Yagüez originates west of Maricao and flows predominately east to west to discharge in the Mayagüez Bay passing through the City of Mayagüez (Figure 4.2.4 and 4.3.1). The Guanajibo River originates along the western side of the Cordillera Central northeast of the Sábana Grande town and south east of Maricao town. It flows predominately north to south towards the Sábana Grande town, and then towards the west up to its mouth in the Mona Passage (Figure 4.2.4). Some of its main tributaries are the Río Rosario, Río Viejo, Río Duey, Río Hoconuco, Río Caín, Río Cupeyes, and Río Flores.

Two gauge stations with reported values of daily mean flow rate are maintained by the USGS at the study area: *50144000 Rio Grande de Añasco near San Sebastian, PR* and *50138000 Rio Guanajibo near Hormigueros, PR* (Figure 4.2.4). Statistics of monthly mean discharge for these stations are presented in Figure 4.3.2. The source data were obtained from Figueroa et al. (2006). For the station located on the Añasco River the statistics correspond to the water years 1963 to 2004, and for the station located on the Guanajibo valley the statistics correspond to the water years 1973 to 2004.

The two rivers present the same pattern, higher monthly mean discharge occur in September and October, while lower values occur in February and March. The higher monthly mean discharge for the Añasco river corresponds to the month of September with a value of 19.71 m^3/s (696 ft^3/s), while the minimum monthly mean discharge values is 3.03 m^3/s (107 ft^3/s) and occurs in March. In the case of the Guanajibo River, the higher monthly mean discharge is 13.08 m^3/s (462 ft^3/s) at September and the minimum occurs in March with a value of 1.27 m^3/s (44.9 ft^3/s). The annual mean value for the water years 1973 to 2004 for the Guanajibo station is 5.44 m^3/s (192 ft^3/s). At the Añasco station, the annual mean values for the water years 1963 to 2004 is 9.43 m^3/s (333 ft^3/s).

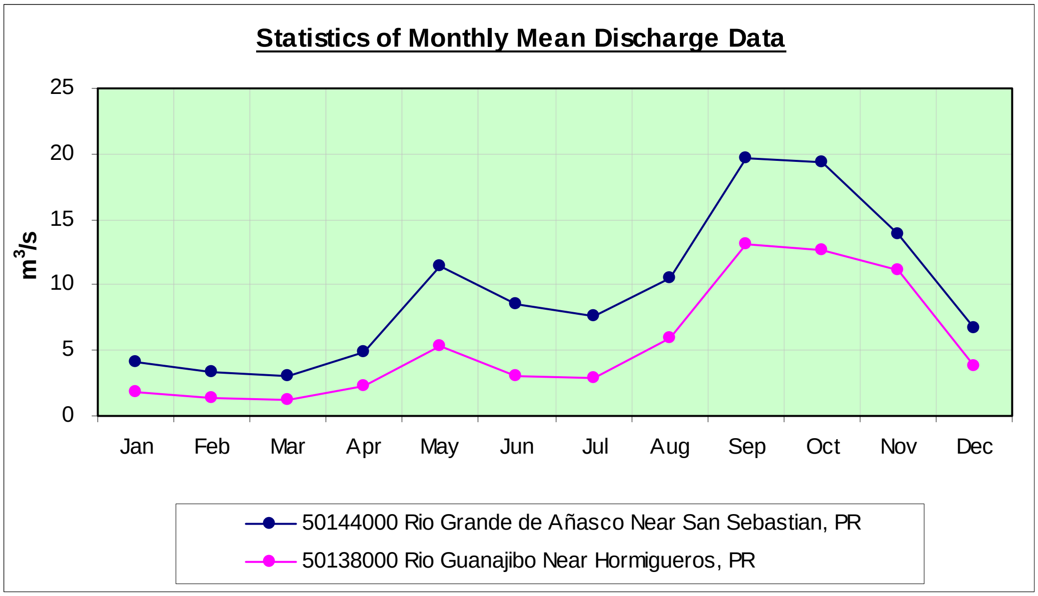


Figure 4.3.2. Statistics of monthly mean discharge data for the 50144000 Rio Grande de Añasco near San Sebastian, PR and 50138000 Rio Guanajibo near Hormigueros, PR stations.

4.4 GEOLOGY AND HYDROGEOLOGY

The Añasco region (located between longitudes 67°15'W and 66°45'W and latitudes 18°20'N and 18°05'N) comprises the Río Grande de Añasco and the Río Yagüez basins. Its surficial geology consists of volcanic and volcaniclastic rocks, plutonic rocks, alluvial, swamp and beach deposits (Figure 4.4.1).

According to Veve and Taggart (1996), the volcanic and volcaniclastic rocks are cretaceous age, and most of them were formed or deposited in a marine environment. They are unconformably overlain by alluvial deposits of quaternary age in the Río Grande de Añasco and lower Río Yagüez valleys. These alluvial deposits consist of clay, silt, sand, and localized gravel deposits (Veve and Taggart, 1996). As it is presented in the Figure 4.4.1, swamp deposits are present in some areas of the Añasco and Yagüez valleys, and beach deposits are present along the coast. Plutonic rocks crop out in patches in some areas of the region.

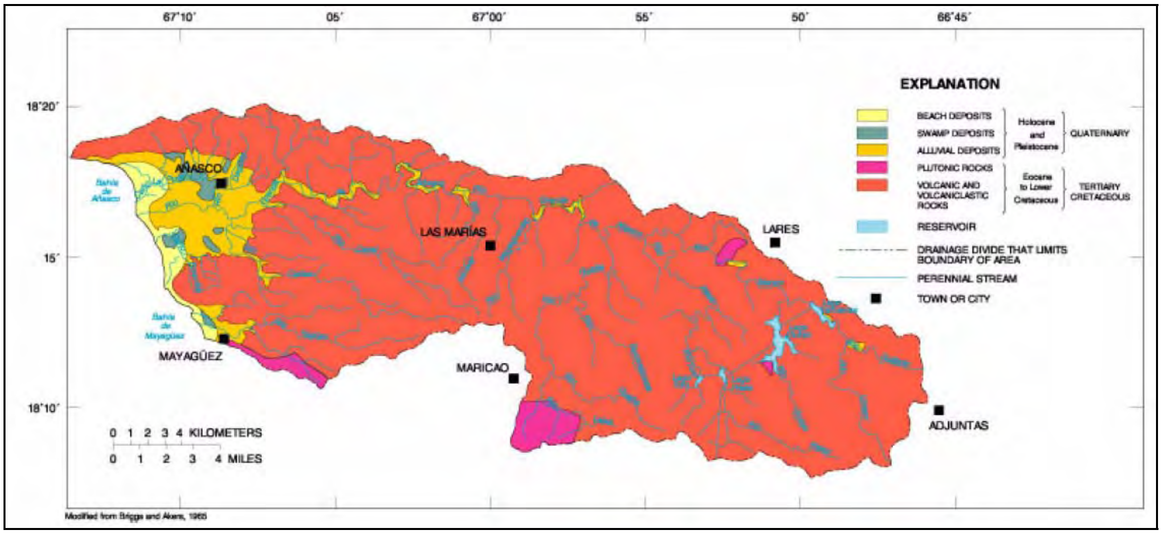


Figure 4.4.1. Generalized surficial geology in the Añasco region (Source: Veve and Taggart, 1996; presented with authorization from the USGS Caribbean Water Science Center).

Diaz and Jordan (1987), present data of five seismic lines run in different parts of the Río Grande de Añasco lower valley, used to locate and describe subsurface materials (Figures 4.4.2 and 4.4.3). This data indicate four subsurface zones of materials as is presented below; well log data were used to help to describe the different materials (Díaz and Jordan, 1987):

- Zone I: Soil and alluvial material above the water table
- Zone II: Saturated alluvium which generally ranges in thickness from 15.2 to 30.5 m (50 to 100 ft) in the central part of the valley; thinning to a featheredge at the bedrock boundaries. This material consists mainly of clay and silt, with some sand, occasional beds of gravel (apparently deposited in former stream channels), swamp deposits and interfingering dune and beach sand near the coast (Díaz and Jordan, 1987).
- Zone III: This zone appears to be present in the central part of the valley underlying the alluvium, and is predominately composed of layers of hard dense clay and soft limestone. The thickness of this zone is as much as 76.2 m (250 ft) and reaches depths as much as 106.7 m (350 ft) (Díaz and Jordan, 1987).
- Zone IV: Mainly composed of rocks of igneous origin (Díaz and Jordan, 1987).

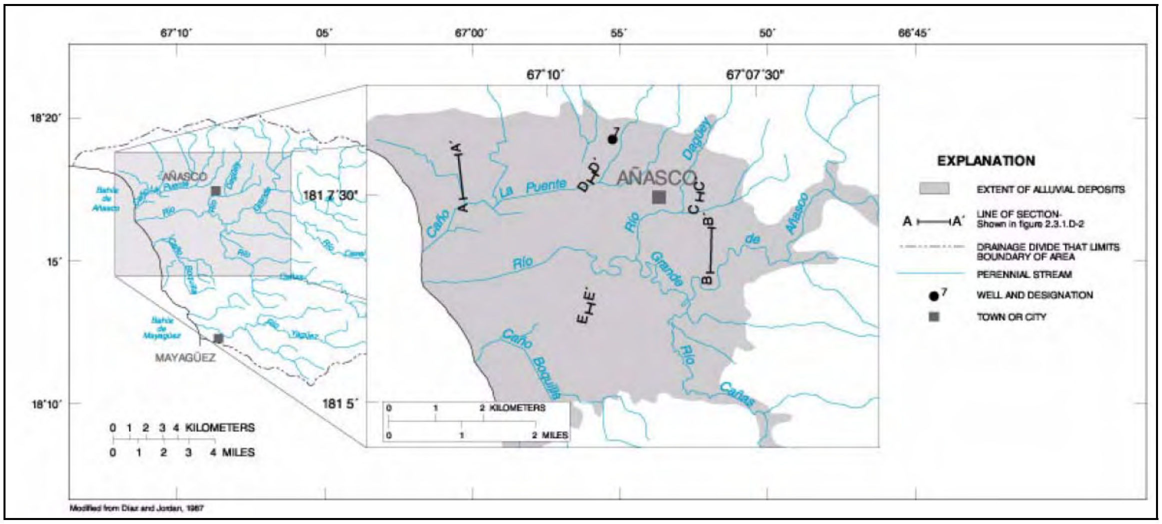


Figure 4.4.2. Location of the seismic profiles in the Río Grande de Añasco lower valley (Source: Veve and Taggart, 1996; presented with authorization from the USGS Caribbean Water Science Center).

According to Diaz and Jordan (1987), there are two water-bearing units in the Río Grande de Añasco lower valley: the alluvium (zone II) and the limestone of zone III. The permeability of the alluvium of zone II is very low given that it is mostly composed of fine grain material. The water yielding zones in the alluvium occur in the layers of sand and gravel where the permeability is higher, and therefore, the yields from wells in this zone depend on the extent the well penetrates these layers (Díaz and Jordan, 1987). According to Díaz and Jordan (1987), the recharge to this zone is largely due to infiltration of rainfall. The altitude of water table in this zone for the dry (February 11, 1982) and wet season (September 3, 1981) were monitored through a network of 30 shallow piezometers in the Río Grande de Añasco lower valley, and presented by Diaz and Jordan (1987). In general the depth to the ground-water table in this zone approximately ranges from about 4.6 m (15 ft) in the east to about 0.6m (2 ft) toward the west (Diaz and Jordan, 1987). The altitude of the water table varies from around 8 m in the upper part of the lower valley to 0.5 – 2 m at wells located 1 km inland from the coast approximately. Variations in the altitude of the water table during the dry and wet seasons are small, and the general pattern of ground-water flow is toward the coast, with local flow components to the Añasco River (Figure 4.4.4).

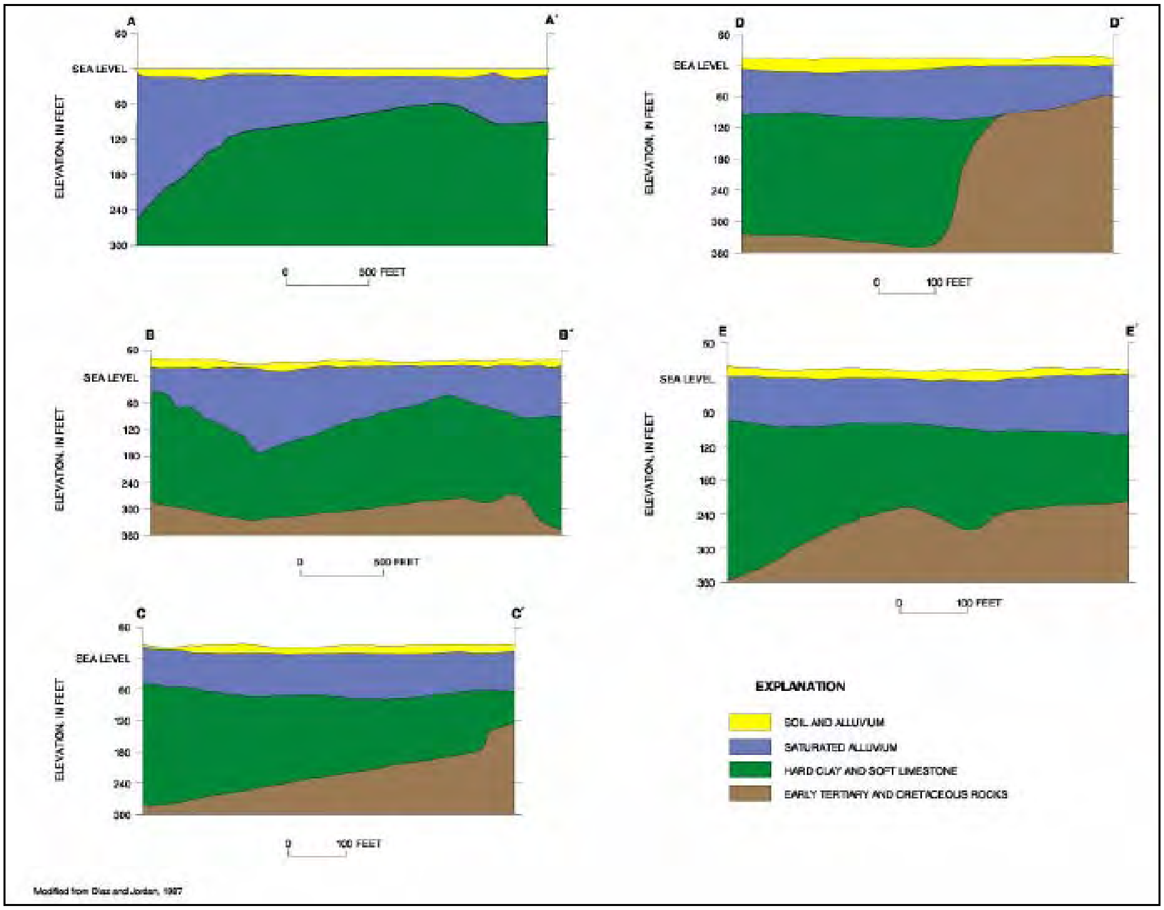


Figure 4.4.3. Subsurface materials cross sections obtained from seismic profiles and well log information in the Río Grande de Añasco lower valley. (Location of sections shown in Figure 5.4.2) (Source: Veve and Taggart, 1996; presented with authorization from the USGS Caribbean Water Science Center).

According to Diaz and Jordan (1987), the location and thickness of the limestone beds of zone III vary greatly. An estimated transmissivity from a pumping test performed in well 7 (Figure 4.4.2) which penetrated 15.24 m (50 ft) in limestone was $2.31*10^{-3}$ m^2/s (2,150 ft^2/d) (Diaz and Jordan, 1987, p. 30). Recharge to zone III is unknown (Díaz and Jordan, 1987). Diaz and Jordan (1987) suggest that the limestone beds could receive recharge from the overlying alluvium in places where the clay is absent; or from the bedrock where the limestone adjoins the valley walls.

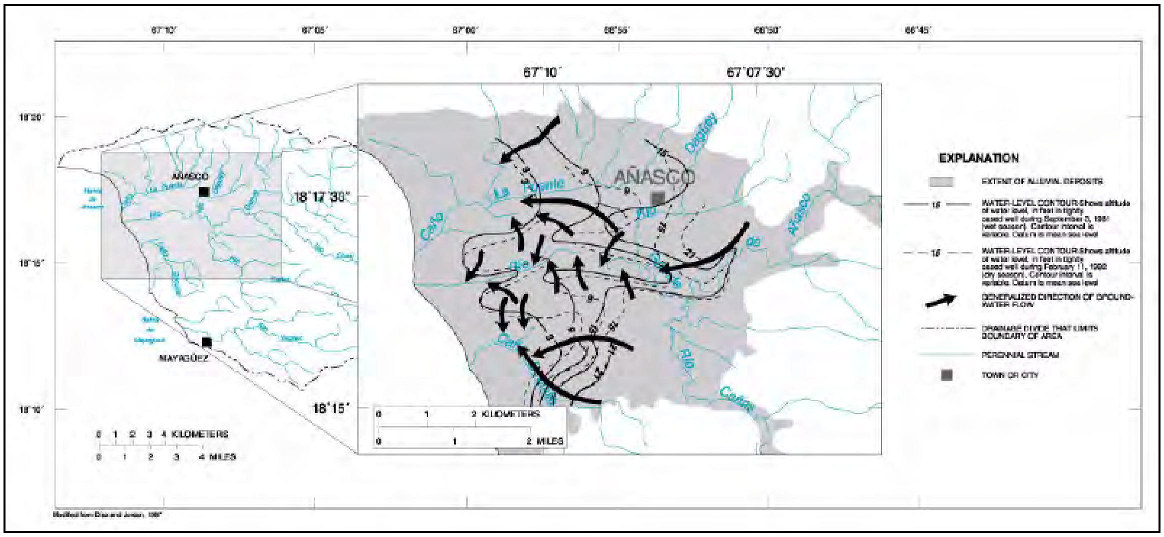


Figure 4.4.4. Altitude of water table in the alluvial aquifer (Zone II) for September 1981 and February 1982, and direction of ground-water flow during September 1981 for the Río Grande de Añasco lower valley (Source: Veve and Taggart, 1996; presented with authorization from the USGS Caribbean Water Science Center).

According to Veve and Taggart (1996), the geology of the Guanajibo region (Figure 4.4.5) consists of four major lithologically distinct groups of rocks:

- Alluvial deposits. Clay predominates near the surface of the alluvium, being underlain generally by beds of sand, sand and clay, or sand and gravel. These deposits overlie the volcanic and volcaniclastic rocks and the Bermeja complex (Veve and Taggart, 1996).
- Limestone formations. They are present overlying the Bermeja complex and variations of the volcanic, volcaniclastic, plutonic and sedimentary rocks; and consist generally of massive to thick-bedded limestone (Veve and Taggart, 1996).
- Volcanic, volcaniclastic, plutonic and sedimentary rocks. These rocks have been folded, faulted, and subject to extreme weather and erosion. They are present principally in the mountains around the central Guanajibo Valley (Veve and Taggart, 1996).
- The Bermeja complex. It is mainly exposed in the southwestern part of the Guanajibo region and consists principally of serpentinite, amphibolite, basalt, and chert (Veve and Taggart, 1996).

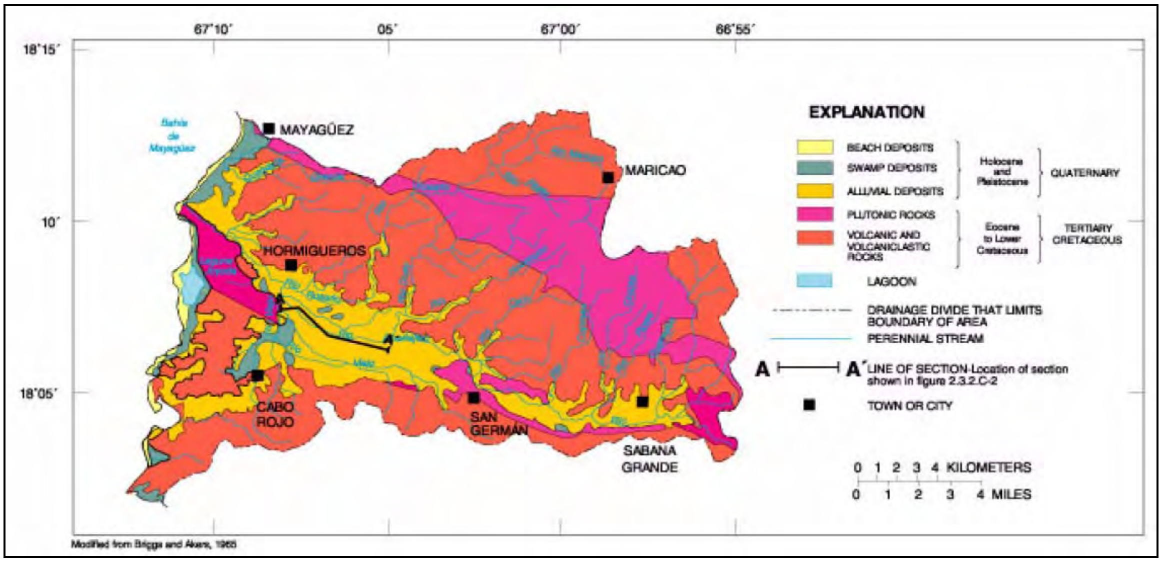


Figure 4.4.5. Generalized surficial geology in the Guanajibo region (Source: Veve and Taggart, 1996; presented with authorization from the USGS Caribbean Water Science Center).

Based on geologic sections (one of them is shown in Figure 4.4.6). Colón-Dieppa and Quiñones-Márquez (1985) state that the alluvium is underlain by limestone or directly by basalt in the central Guanajibo valley, and that limestone is not present in the eastern and northern parts of the central valley. Within the alluvium, generally clay is near the surface, underlain by sand, sand and clay and sand and gravel lenses (Colón-Dieppa and Quiñones-Márquez, 1985).

Surface resistivity surveys and seismic tests were used in conjunction with well logs to study the nature and thickness of the materials in the central Guanajibo valley, to assist in defining the type of materials, extent of formations, and depth at which potential aquifer occur (Colón-Dieppa and Quiñones-Márquez, 1985). The tests showed that the alluvium is about 21.3 m (70 ft). Limestone is underlying the alluvium, being more than 61 m (200 ft) thick in the central Guanajibo Valley, and is thicker near Cabo Rojo. An estimate of the depth to relatively impermeable bedrock through the valley was estimated from the driller’s logs and the resistivity and seismic profiles (Colón-Dieppa and Quiñones-Márquez, 1985) (Figure 4.4.7).

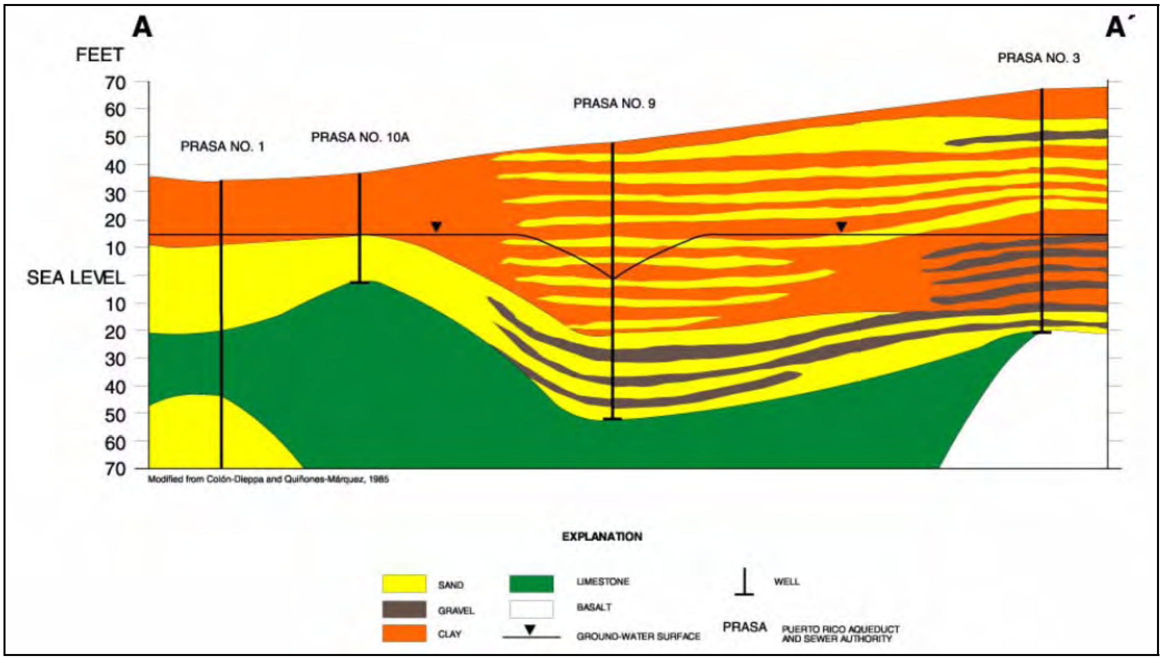


Figure 4.4.6. Geologic section A-A' in the central Guanajibo valley (location of cross section shown in the Figure 4.4.5) (Source: Veve and Taggart, 1996; presented with authorization from the USGS Caribbean Water Science Center).

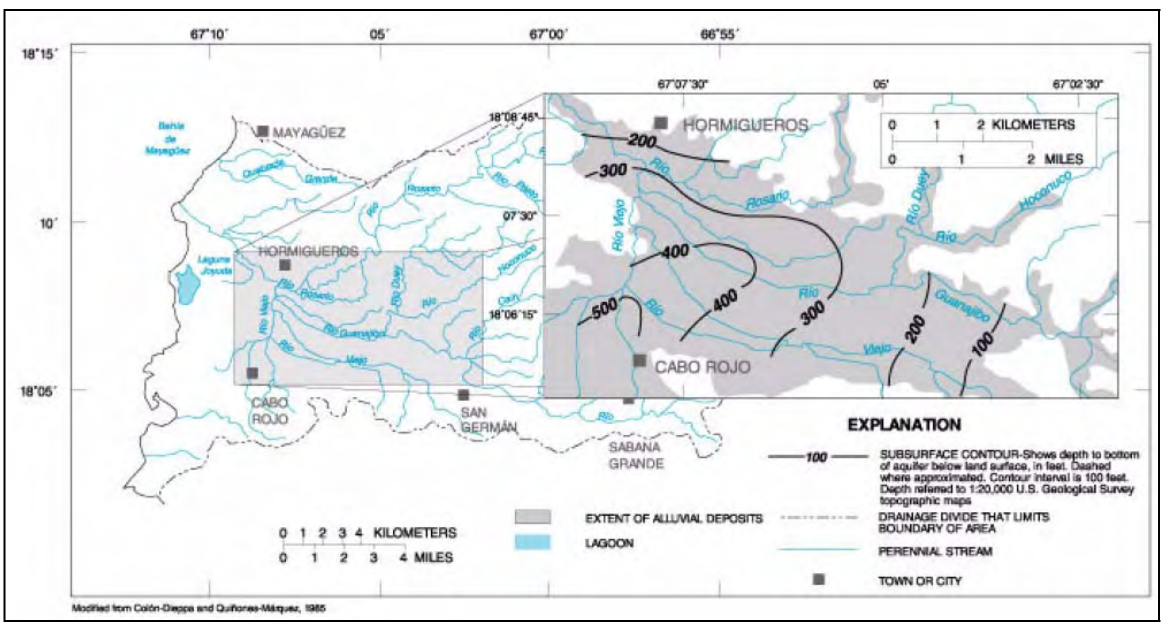


Figure 4.4.7. Approximate depth to the relatively impermeable bedrock in the central Guanajibo valley (Source: Veve and Taggart, 1996; presented with authorization from the USGS Caribbean Water Science Center).

According to Colón-Dieppa and Quiñones-Márquez (1985), ground-water occurs in fractured and porous limestone underlying the alluvium, and in sand and gravel deposits within the alluvium; and where volcanic and other igneous rocks are highly fractured, they may serve as locally important aquifers. Given that clay overlies most of the valley, significant direct recharge from rainfall is not probable, and most of the recharge to the aquifer is believed to occur principally along the contact between the alluvium and the igneous rocks (Colón-Dieppa and Quiñones-Márquez, 1985). The limestone, sand and gravel deposits are more abundant in the west and southwest part of the central Guanajibo valley and clay is more abundant in the east and north (Colón-Dieppa and Quiñones-Márquez, 1985).

A generalized water-table contour map of the central Guanajibo valley during June 1980 was constructed from water level measurements of 23 wells by Colón-Dieppa and Quiñones-Márquez (1985) (Figure 4.4.8). In areas where wells were sparse, the ground-water gradient was assumed to approximate the land surface gradient (Colón-Dieppa and Quiñones-Márquez, 1985). Figure 4.4.8 shows that the general pattern of ground-water flow during June 1980 was from the mountains surrounding the valley to the central part near the Guanajibo River, and then toward the coast. According with Jesús Rodríguez (USGS), the units of the water-table contours in Figure 4.4.8 are meters above mean sea level, and not feet as stated in the legend of that figure (personal communication, Jesús Rodríguez Martínez (USGS), April 23, 2007).

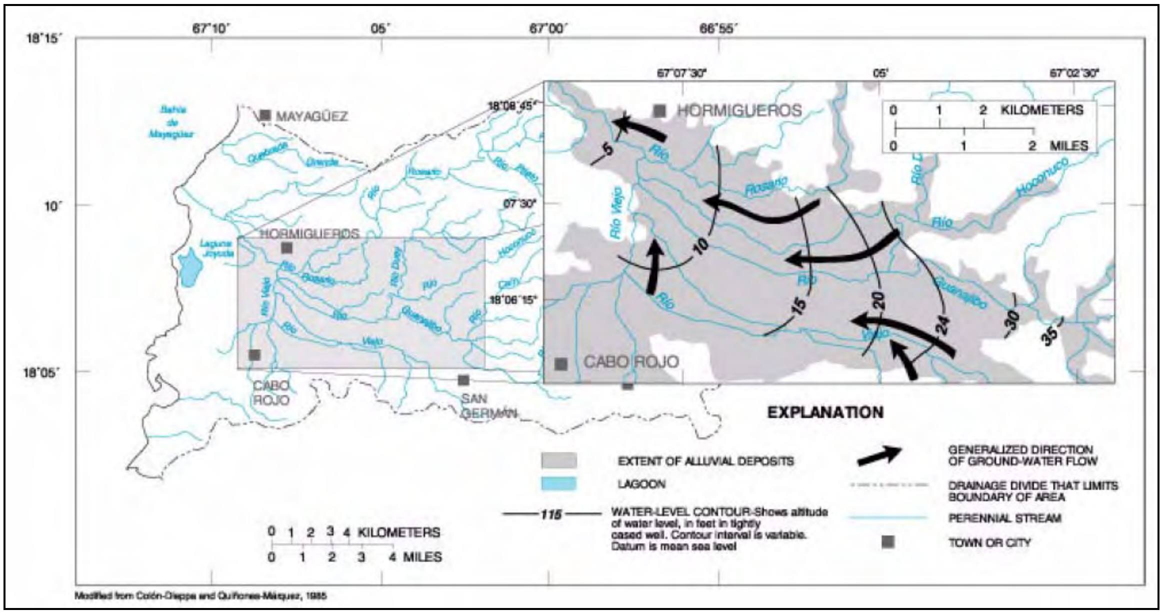


Figure 4.4.8. Altitude of water-level surface and direction of ground-water flow during June 1980 (Source: Veve and Taggart, 1996; presented with authorization from the USGS Caribbean Water Science Center).

Rodríguez et al. (2004) divided the Mayagüez municipality into five (5) hydrogeologic terrains according with their hydrogeologic characteristics and ground-water development potential. Brief description of these terrains is presented next, based on the reference Rodríguez et al. (2004). One of these terrains is the MayHT1 which is restricted to the lowlands that includes the coastal plain and the narrow bands of alluvium along the rivers in the mountainous interior of the municipality (including the Yagüez lower valley). This terrain consists of two zones: upper and lower (Rodríguez et al., 2004).

The upper zone is mostly composed by alluvium, and to a lesser extent mangrove and swamp deposits (Rodríguez et al., 2004). The alluvium is mostly composed of silt and clay and minor amounts of sand. Minor gravel and sand deposits can occur at some parts. According to Rodríguez et al. (2004), the thickness of this zone can range from 15.2 m (50 ft) to 30.5 m (100 ft) thinning towards the rock outcrops. In this zone ground-water occurs under water-table conditions; the depth to the water table is generally less than 3 m (10 ft) below land surface; the fluctuations of the potentiometric surface between wet and dry seasons generally is less than 1.5 m (5 ft) (Rodríguez et al., 2004). Rodríguez et al. (2004), state in their study that the ground-water development of this zone in the southern part of the Añasco lower valley has been minimal and the ground-water levels have remained essentially the same since the 1987 study of Diaz and Jordan, and therefore it could be assumed that ground-water flow patterns at that area have remained the same. South to that area, according to Rodríguez et al. (2004), a predominant ground-water movement may occur westward with probable local flow components toward nearby streams. The yield to wells in this zone depends on the amount of sand and gravel penetrated. Precipitation is the main source of recharge to this unit (Rodríguez et al., 2004).

According to Rodríguez et al. (2004), the lower zone consists of sandstone, volcaniclastic and limestones, and is underline by igneous rocks and serpentinite. The thickness of the sandstone, volcaniclastic and limestone is unknown, and they are presumed to be discontinuous and of limited extend. The limestone varies in thickness and vertical position, and can be intercalated with gravel and sand beds. Confined and semiconfined conditions have been found, and could be explained by the irregular distribution of permeable and non permeable materials (vertically and horizontally). Also, as a result of this irregular distribution, the ground-water flow pattern is complex in this zone (Rodríguez et al., 2004). However, a dominant regional westward movement is suggested by limited data collected (Rodríguez et al., 2004). According to Rodríguez et al. (2004), the upper unit can become a semiconfining unit (for the lower zone) where it is thick. Recharge to the lower zone is not well known. The most important water bearing unit in this zone is the limestone. The thickness and spatial distribution of the water-bearing and the confining/semiconfining units is not well known (Rodríguez et al., 2004).

The remaining area of the Mayaguez municipality is divided in 4 hydrogeologic terrains, according to Rodríguez et al. (2004), consisting mostly of volcaniclastic and igneous intrusive rocks (MayHT2 and MayHT3), serpentinite rocks (MayHT4), and igneous intrusive rocks (MayHT5). Limited lithologic and hydrogeologic data suggest the ground-water could occur under confined conditions in some areas (MayHT3) (Rodríguez et al., 2004). Depth to water below land surface has been found in the range of 1.8 m (6 ft) (MayHT3) to 33.2 m (109 ft) (MayHT4); and also there is presence of springs in some locations (Rodríguez et al., 2004). Artesian conditions in Cerro Las Mesas (MayHT4) may result from intersection of dipping fractures (Rodríguez et al., 2004). According to Rodríguez et al. (2004), recharge to the fractured aquifer in this terrain (MayHT4) is not well understood; one possible mechanism could be the downward movement of water from storage in the overlying soil layer; another could be direct infiltration through exposed fractures.

5 MODEL CONCEPTUALIZATION

Translating the entire physical system into one that can be modeled numerically is a very important part of the hydrologic modeling process. The conceptualization of an integrated hydrological model includes the main processes and storage compartments of the hydrologic cycle. This section presents the model conceptualization for the study area. Also, proposed model parameter initial values, boundary and initial conditions, and references to the source data used in this study to help in the conceptualization are included in this section. Note that the aim of this model, once it is refined in future studies, will become a first preliminary step to evaluate alternatives to perform gross estimations of the annual water budget at a regional scale.

5.1 TOPOGRAPHY

Land elevation data for the study area was provided by the USGS. The USGS topographic contours for Puerto Rico (Figure 5.1.1) were used to represent the land elevations in the model. These data were derived from USGS Digital Line Graph (DLG) data which in turn were converted to digital from USGS 1:20,000-scale topographic Puerto Rico quadrangle maps.

5.2 PRECIPITATION

Hourly rainfall data were obtained from nine (9) stations located within the study area and aggregated in a daily basis. Seven (7) of those are USGS stations, one is from the NRCS and the other one is from the USDA Tropical Agriculture Research Station (TARS) located adjacent to the UPR Mayagüez Campus (UPRM). Also, data from another station located at Civil Engineering Building - UPRM (source: Professor R. Zapata, UPRM) were used to fill missing data at the TARS station. The data for the stations were obtained from: USGS (personal communication, Ana Sánchez (USGS), March 21, 2006), NRCS, and UPRM (personal communication, Eric Harmsen (UPRM), 4 May 2006). The location of the stations is presented in Figure 5.2.1. To account for the spatial distribution of rainfall, Thiessen polygons were delimitated for the study area (Figure 5.2.1).

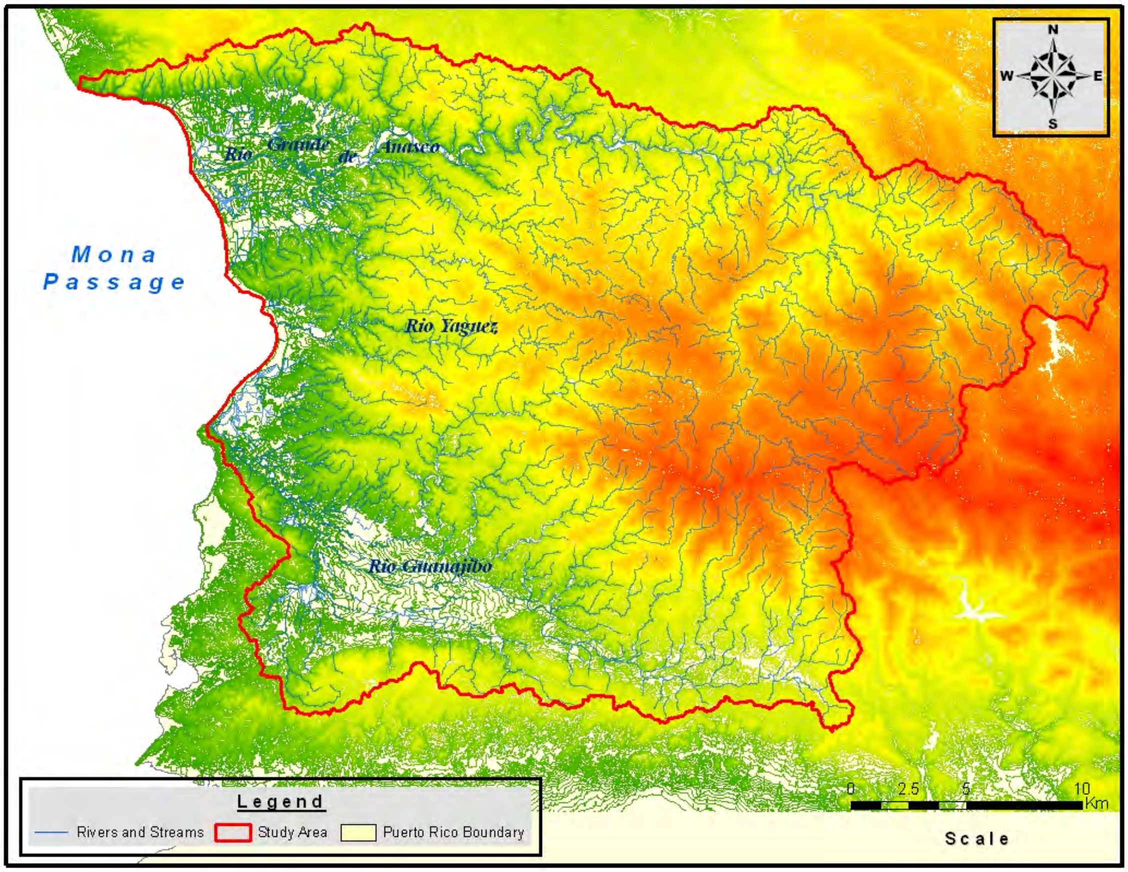


Figure 5.1.1. USGS topographic contours for the study area.

The year 2004 was selected as the period to perform preliminary runs once the model was implemented in the numeric model. Periods where there was no data were filled with the records from other station located in the study area as shown in Table 5.2.1.

An analysis was performed to do an estimation of the 2004 annual volume of water from precipitation, and the average 2004 annual precipitation over the study area based on the Thiessen polygon approach (Table 5.2.2). A total volume of 1,567,922,641 m^3 was obtained from precipitation during 2004, and the average 2004 annual precipitation over the study area is 1,910 mm according with this analysis.

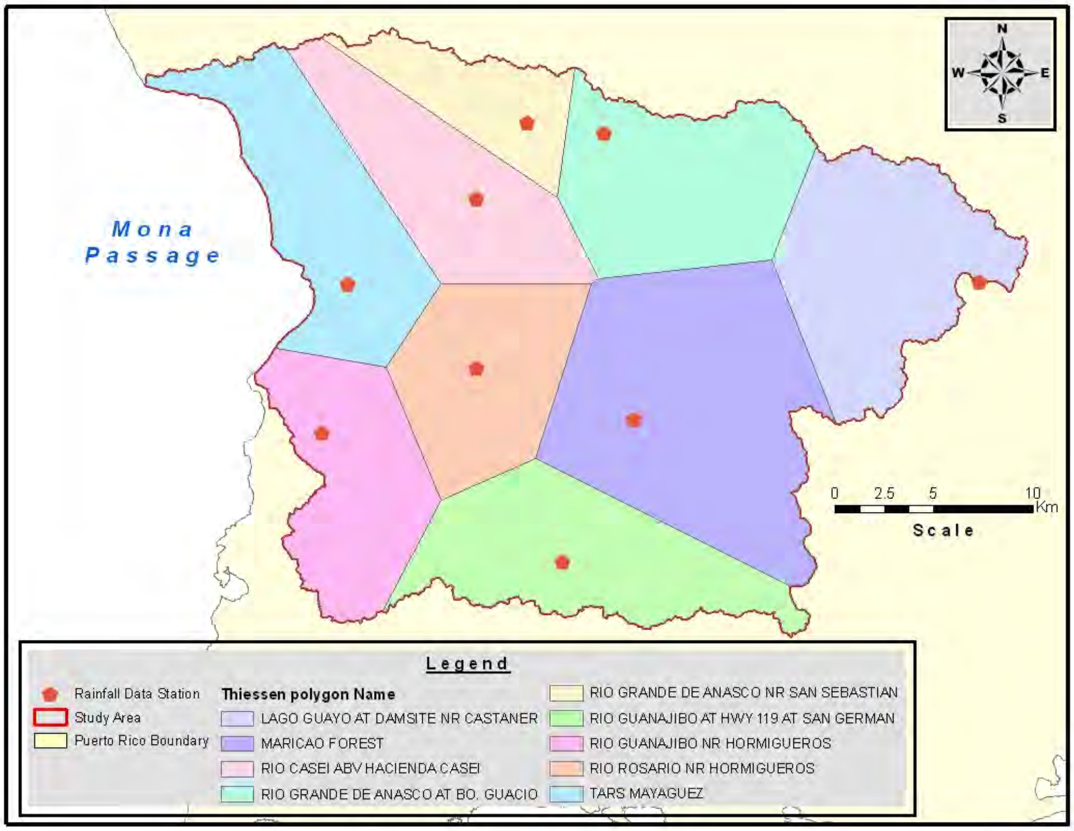


Figure 5.2.1. Location of the rainfall data stations and Thiessen polygons.

Table 5.2.1. Rainfall stations used in this Study.

STATION	USGS ID	SOURCE	Missing Data (days)	STATION USED TO FILL MISSING DATA
RIO GRANDE DE ANASCO AT BO. GUACIO	50143930	USGS	0.8	RIO GRANDE DE ANASCO NR SAN SEBASTIAN
RIO GUANAJIBO NR HORMIGUEROS	50138000	USGS	0.8	Mayaguez TARS
RIO GRANDE DE ANASCO NR SAN SEBASTIAN	50144000	USGS	0.9	RIO GRANDE DE ANASCO AT BO. GUACIO
RIO ROSARIO NR HORMIGUEROS	50136400	USGS	1.0	RIO CASEI ABV HACIENDA CASEI
LAGO GUAYO AT DAMSITE NR CASTANER	50141500	USGS	2.1	RIO GRANDE DE ANASCO NR SAN SEBASTIAN
TARS MAYAGUEZ	NA	TARS	3.0	Mayaguez UPRM
RIO CASEI ABV HACIENDA CASEI	50145395	USGS	8.0	RIO GRANDE DE ANASCO NR SAN SEBASTIAN
RIO GUANAJIBO AT HWY 119 AT SAN GERMAN	50131990	USGS	44.7	RIO GUANAJIBO NR HORMIGUEROS
MARICAO FOREST	NA	NRCS	75.6	RIO ROSARIO NR HORMIGUEROS

Table 5.2.2. Estimation of the 2004 annual volume of water from precipitation for the study area.

Polygon name	P_{annual} (mm)	Area (km^2)	Volume (m^3)
RIO GRANDE DE ANASCO AT BO. GUACIO	2,200.66	94.39	207,725,275.14
RIO GUANAJIBO NR HORMIGUEROS	1,148.84	77.85	89,440,416.82
RIO GRANDE DE ANASCO NR SAN SEBASTIAN	2,195.83	42.27	92,822,370.57
RIO ROSARIO NR HORMIGUEROS	2,353.82	74.84	176,163,734.25
LAGO GUAYO AT DAMSITE NR CASTANER	1,562.86	102.19	159,714,783.35
TARS MAYAGUEZ	1,991.61	91.91	183,051,979.91
RIO CASEI ABV HACIENDA CASEI	2,151.13	79.57	171,158,170.14
RIO GUANAJIBO AT HWY 119 AT SAN GERMAN	1,120.14	95.93	107,457,520.35
MARICAO FOREST	2,375.41	160.14	380,388,390.51
	Total =	**819.10**	**1,567,922,641.03**

$$\overline{P}_{2004annualaverage} = \frac{1{,}567{,}922{,}641.03m^3}{819{,}099{,}031.10m^2} = 1.91m = 1{,}910.00mm = 75.20in$$

Where $\overline{P}_{2004annualaverage}$: Average 2004 annual precipitation over the study area

5.3 SURFACE WATER

The implementation of the present model is based on two approaches for surface water flow: the simulation of the Añasco and Guanajibo main channel rivers with the numerical model Mike 11 (see next chapter); and the use of Mike She to simulate overland flow everywhere else over the study area.

5.3.1 Land cover classification and spatial distribution

A digital map of the forest type and land cover developed for Puerto Rico from a segmented, supervised classification approach using Lansat TM imagery (Helmer et al., 2002) was used to conceptualize the different land cover categories present over the study area. This data was provided by the United States Department of Agriculture (USDA) and is presented in Figure 5.3.1. The spatial resolution of this map is 30 m.

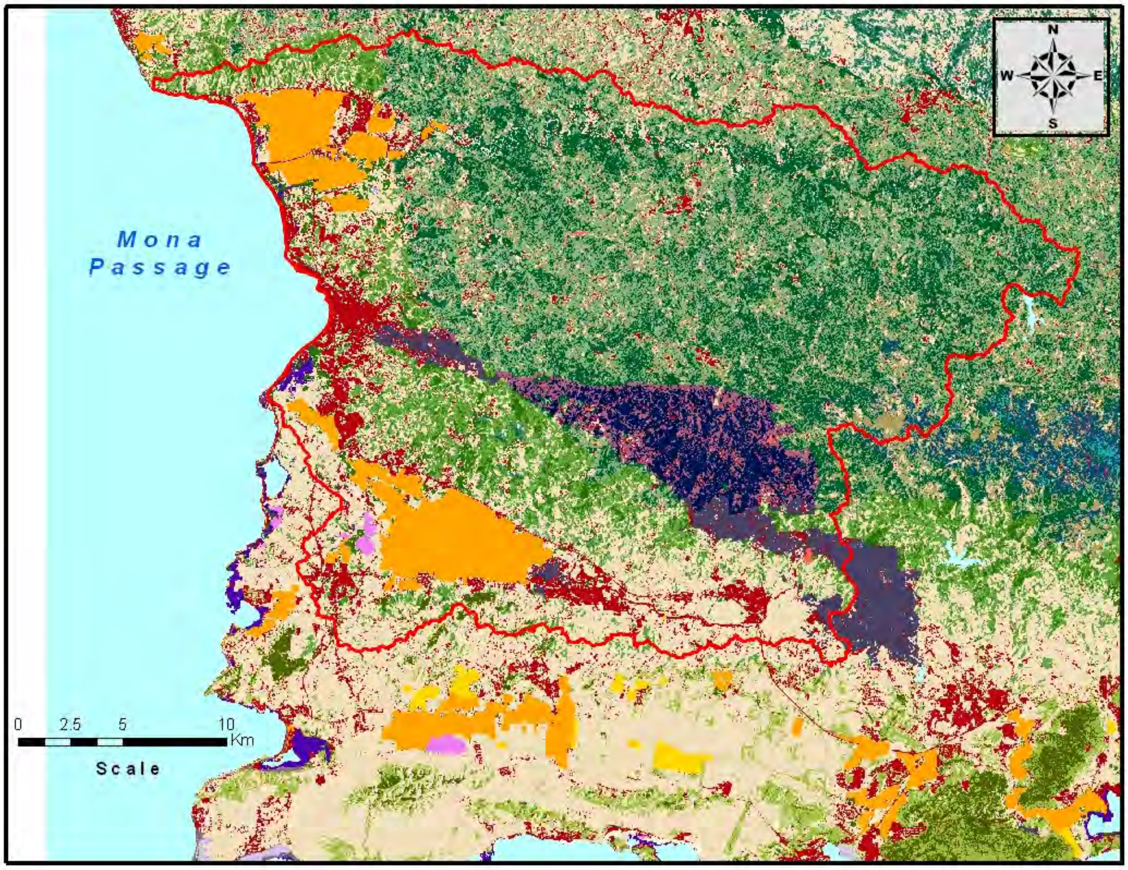


Figure 5.3.1. Western area of the Land cover and forest formation map of Puerto Rico, 1991-92 (Original data source: Helmer et al., 2002).

Twenty five (25) different classes of land cover and forest type are present over the study area (Figure 5.3.1), sixteen (16) of them corresponding to different kind of forest, shrubland, woodland, or shade coffee. This map was reclassified into six (6) categories of land cover for the purpose of this study as shown in Table 5.3.1 and Figure 5.3.2. There are several reasons to perform this aggregation of land cover classes into major categories for this study, some of them are:

- The classification of land cover in this conceptual model is used to assign values for physical based parameters which will be important in the simulation of the following processes: overland flow (Manning's n), rainfall interception (Leaf Area Index (LAI)), and evapotranspiration (Root Depth (RD), and Crop Coefficient (K_c)). Reported literature values for those parameters are very scarce and frequently nonexistent for many of the land cover classes of the map presented in Figure 5.3.1.
- In the preprocessing stage of data during the implementation of the model in the numeric engine, the land cover map will be interpolated to a grid of cells of 200 X 200 m size each, which would imply a reassignment of categories for many of the smaller polygons presented in Figure 5.3.1 (with the consequent reassignment of parameter values) without the control of the modeler. For that reason, for example, water class was reclassified into forest, shrub, woodland, or shade coffee. Most of the polygons within the study area classified as water in the source information were relatively small and surrounded mostly by forest. During the interpolation to the model grid, there would be the possibility that cells (200 X 200 m) were assigned the category water, when most of the cell could be in fact forest.
- The numerical model will demand large computer resources. Computational time increases with the number of land use polygons. Therefore it is desirable to have as simple a conceptual model as possible to decrease the computational time of simulations.
- The regrouping of similar land cover classes into major categories is not expected to produce great impacts in the results of the annual water balance estimation once the model is calibrated and validated. However, this assumption should be verified in future studies.

Figure 5.3.3 shows the percentage distribution of land cover categories over the study area according to the reclassification. Forest, shrub, woodland and shade coffee is the category which covers more area (64.6 %), followed by pasture with 21.1 %. Quarries, sand and rock and Emergent wetlands (including seasonally flooded pasture) cover a small percentage of the area with 0.1 and 0.2 %, respectively. Forest is mainly distributed over the central and east zones of the study area. Urban areas are present in the Mayagüez, Añasco, San Germán, Sábana Grande, Cabo Rojo, Hormigueros, Maricao, and Las Marías urban centers mainly. Agriculture is present in the central Guanajibo and lower Añasco valleys.

Table 5.3.1. Reclassification of the land cover classes.

LAND COVER CLASS	RECLASSIFIED LAND COVER CATEGORY
Active sun/shade coffee, submontane and lower montane wet forest/shrub	Forest, shrub, woodland and shade coffee
Lower montane wet evergreen forest - elfin cloud forest	
Lower montane wet evergreen forest - mixed palm and elfin cloud forest	
Lower montane wet evergreen forest - tall cloud forest	
Lowland dry and moist, mixed seasonal evergreen sclerophyllous forest	
Lowland dry semideciduous forest	
Lowland dry semideciduous woodland/shrubland	
Lowland moist seasonal evergreen and semi-deciduous forest	
Lowland moist seasonal evergreen and semi-deciduous forest/shrub	
Lowland moist seasonal evergreen forest	
Lowland moist seasonal evergreen forest/shrub	
Submontane and lower montane wet evergreen forest/shrub and active/abandoned shade coffee	
Submontane and lower montane wet evergreen sclerophyllous forest	
Submontane and lower montane wet evergreen sclerophyllous forest/shrub	
Submontane wet evergreen forest	
Tidally and semi-permanently flooded evergreen sclerophyllous forest	
Water	
Pasture	Pasture
Urban and barren	Urban and barren
Agriculture	Agriculture/hay
Agriculture/hay	
Other emergent wetlands (including seasonally flooded pasture)	Emergent wetlands (including seasonally flooded pasture)
Quarries	Quarries, sand and rock
Sand and rock	

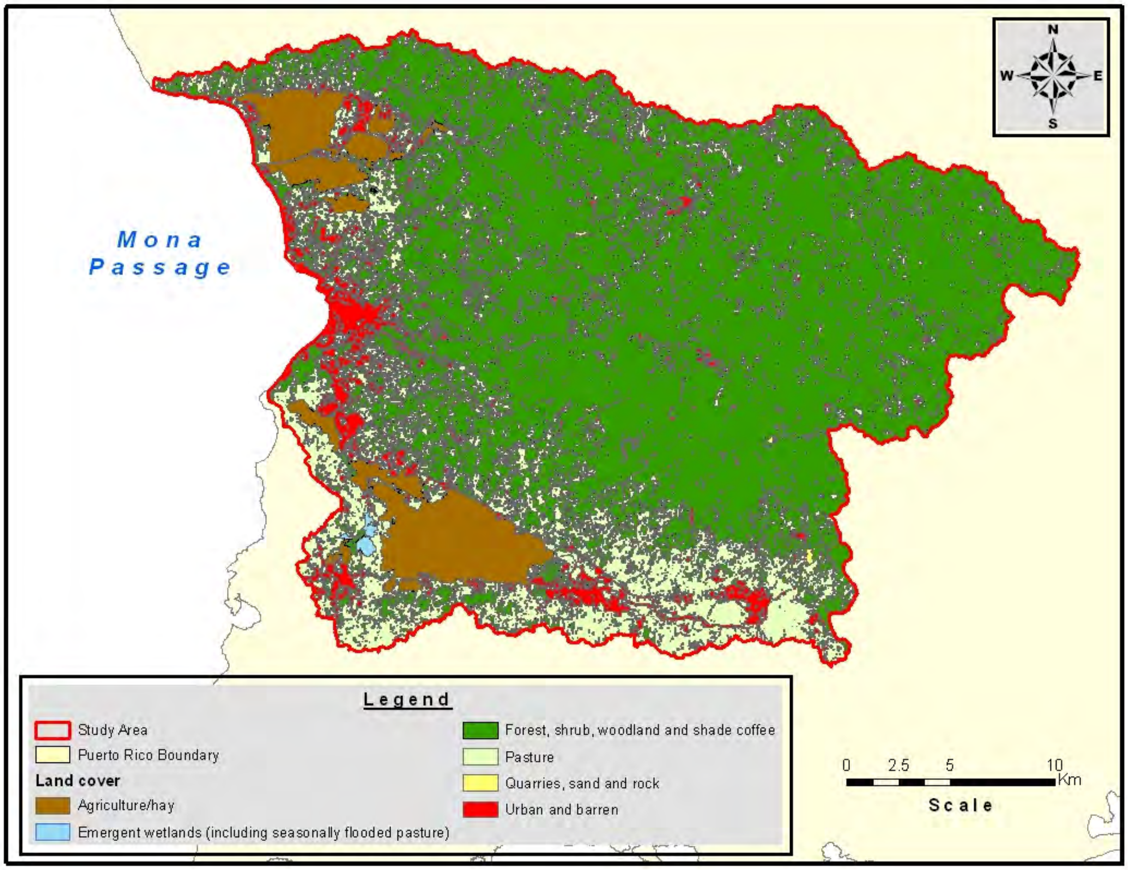


Figure 5.3.2. Conceptualization of the land cover for the study area.

LAND COVER CATEGORY	AREA (Km^2)	AREA (%)
Forest, shrub, woodland and shade coffee	529.16	64.6
Pasture	172.84	21.1
Urban and barren	60.02	7.3
Agriculture/hay	55.06	6.7
Other emergent wetlands (including seasonally flooded pasture)	1.26	0.2
Quarries, sand and rock	0.75	0.1
Total =	**819.10**	**100.00**

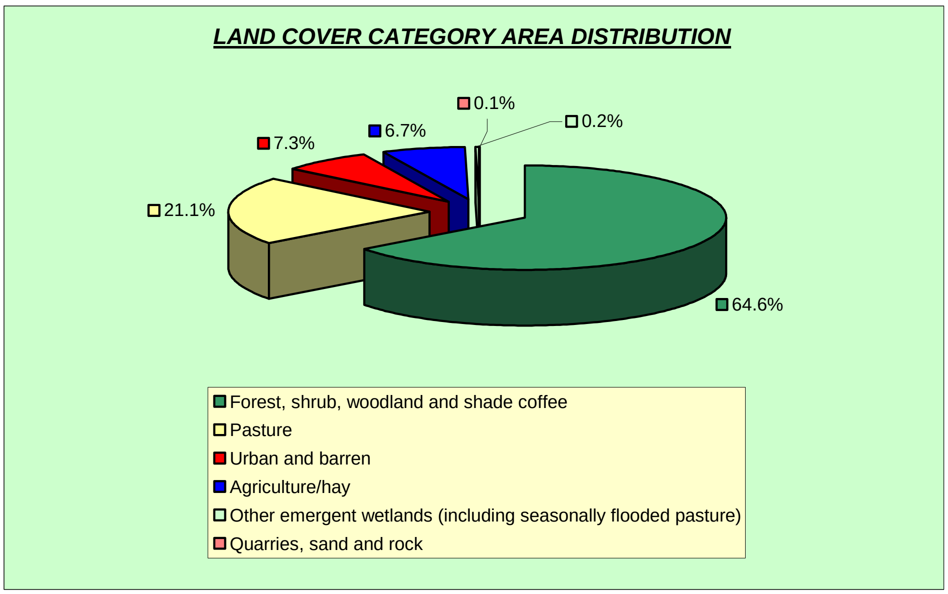


Figure 5.3.3. Land cover category area distribution.

5.3.2 Overland flow parameters

5.3.2.1 Manning's roughness coefficient

The approach proposed for modeling overland flow in this study requires the specification of a roughness coefficient which represents the water flow resistance over different surfaces. Manning's M is defined as the reciprocal of Manning's n, commonly used in the literature. Initial values for this coefficient were proposed for the different land cover categories conceptualized for the study area (Figure 5.3.2), taking into account values presented in the literature by Downer and Ogden (2002a), and Jaber and Shukla (2004). However, those reported values are not for the specific conditions of the study area, and not always corresponded exactly with the categories conceptualized in this study. Therefore, they should be used just as guidelines for initial values. Consequently, the parameter values proposed in Table 5.3.2 have to be considered just as a starting point for initial values of parameters which will be subject to adjustments during future calibration efforts.

Some Manning roughness coefficients (Manning's n) ranges shown by Downer and Ogden (2002a) are: forest: 0.184 – 0.198[1]; pasture: 0.235 – 0.40[2]; grass and pasture: 0.050 – 0.150[3]; concrete or asphalt: 0.010 – 0.150[2]; developed/industrial: 0.0137[4]; row crops 0.070-0.200[3]; small grain: 0.100-0.400[3]; bare sand: 0.010 – 0.016[3]; graveled surface: 0.012 – 0.030[3]. Values of 0.14 and 0.2 were used by Jaber and Shukla (2004) for impoundment depending on degree of vegetation density.

Table 5.3.2. Initial values assumed for the overland flow Manning's n and M parameters.

RECLASSIFIED LAND COVER CATHEGORY	Proposed initial values	
	Manning's n	Manning's M
Forest, shrub, woodland and shade coffee	0.19	5.24
Pasture	0.23	4.44
Urban and barren	0.08	12.50
Agriculture/hay	0.24	4.26
Emergent wetlands (including seasonally flooded pasture)	0.17	5.88
Quarries, sand and rock	0.02	50.00

5.3.2.2 Detention storage

A uniform spatially distributed detention storage value of 4 mm was used for the entire watershed. This value is in the typical range reported in the literature (Downer and Ogden, 2002a) and used in other studies (Ondracek, 2005; Chalkidis et al., 2004).

[1]Senarath et al (2000, cited by Downer and Ogden, 2002a)
[2]USACE (1985, cited by Downer and Ogden, 2002a)
[3]Engman (1986, cited by Downer and Ogden, 2002a)
[4] Downer (2002b, cited by Downer and Ogden, 2002a)

5.3.2.3 Initial water depth

An initial water depth uniform spatial distribution of zero meters over land elevation was assumed for the study area for the first preliminary run of the numeric model presented in next chapter. For subsequent simulations, a hot start process was performed to account for initial conditions.

5.3.3 River network

The Río Añasco and Río Guanajibo rivers were taken into account in this model by including their main channel to be simulated in the numerical model Mike 11. They were selected to be modeled in Mike 11 because continuous flow rate stations are installed in their main channels, and continuous records of flow rate exist at those locations. This permitted to make comparisons between simulated and observed discharge values at the locations of the gauging stations. Also, these are the most important rivers in the study area. The surface water flow for the other streams in the area was taken into account in the model by simulating them as overlandflow. The delimitation of the main channel of these two rivers was taken from the USGS Topographic quadrangles (Figure 5.3.4).

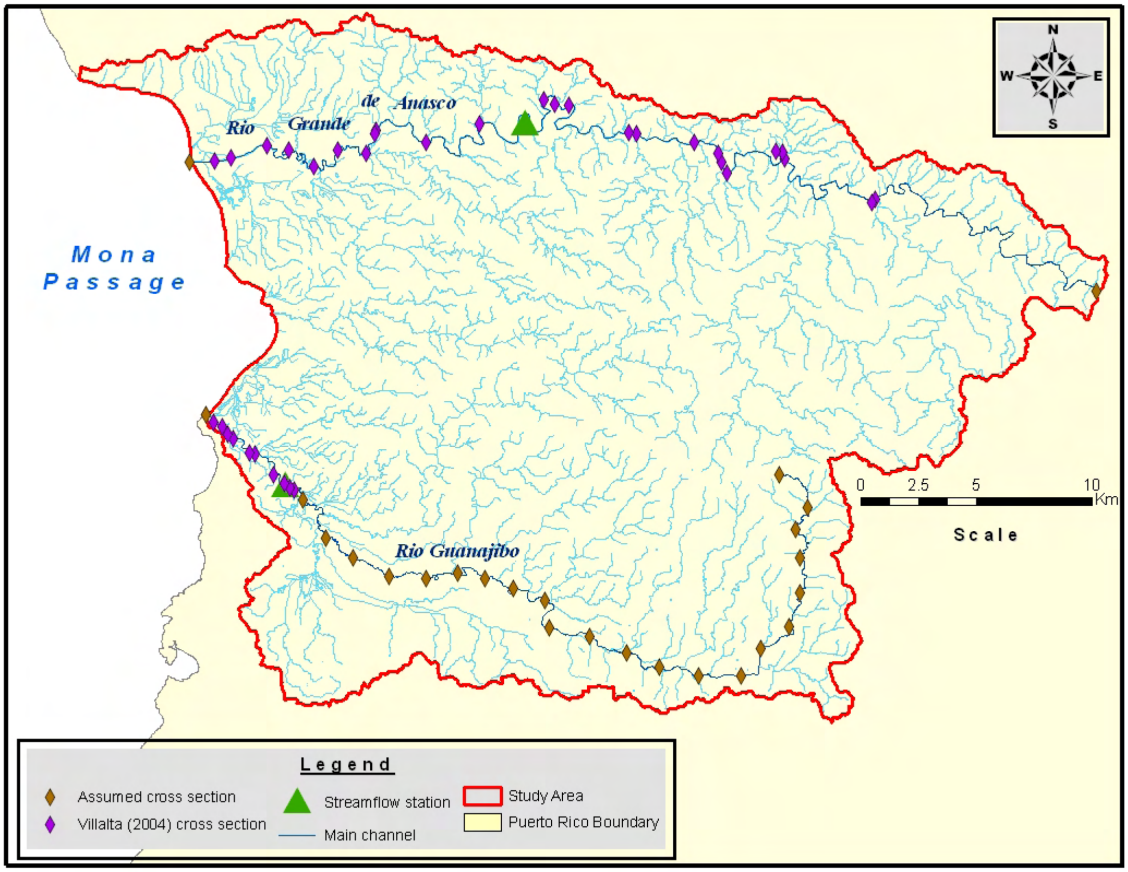


Figure 5.3.4. Location of the reported daily mean discharge data stations and cross sections used.

Available cross section data for these rivers were obtained from Villalta (2004). Unfortunately, these data do not include cross section information at the mouths or the top ends of the rivers. Also, these data only have cross section information for a reach of the Guanajibo River near the coast, and do not include cross section data for most of the length of the main channel of this river (Figure 5.3.4). Because of this, assumed cross section data was used for several locations. The shape of the Villalta's (2004) most upstream cross section for each river was assumed to be the same for the top end location of each river respectively. The altitude of those cross sections was assumed by looking at the elevation contour of the USGS topographic quadrangles at those locations. Cross section data for the Añasco mouth were provided by Alejandra Rojas (personal communication, UPRM, September 21, 2006). At the Guanajibo mouth location, cross section shape was assumed to be the same as the most downstream cross section available from Villalta (2002). The elevation of the left bank of the cross sections at the mouths of both rivers were assumed as 1 m over mean sea level, as no more than the USGS topographic quadrangles elevation information was available. Given the large reach in which there is no cross section data available for the Guanajibo River, twenty one (21) cross sections were assumed at locations along this river between the top end and the most upstream cross section available from Villata (2004). This allowed having a better idea of the slope of this river in that reach for simulation purposes. The shape of all of those cross sections were assumed to be the same as the most upstream one available from Villalta (2004) for that river, and the elevation of the left bank of each one of them was assumed by looking at the elevation contours of the USGS topographic quadrangles at each location. The location of the cross sections is shown in Figure 5.3.4.

Boundary conditions were established at the top end and the mouth of both rivers, as is typically done in catchment models (Written communication, Douglas Graham (DHI), September 25, 2006). A constant inflow of 0.01 m^3/s was established as boundary condition at the top end locations for both rivers. This boundary was established to avoid low water conditions which could cause instabilities in the numerical model (Written communication, Maria Loinaz (DHI), November 16, 2006). The minimum daily mean discharge at the two streamflow stations located in the Añasco and Guanajibo rivers (*50144000 Rio Grande de Añasco near San Sebastian, PR* and *50138000 Rio Guanajibo near Hormigueros, PR*) for the year 2004 (this will be the selected year used in this study to perform preliminary runs of the model); corresponds to 1.926 m^3/s (68 ft^3/s) and 1.161 m^3/s (41 ft^3/s) respectively. The inflow discharge used (0.01 m^3/s) represents only the 0.52% and the 0.86% of those values respectively. Therefore, this discharge is expected not to have significant effects on the results. However, if future studies attempt to calibrate the model, the significance of this value should be verified depending of the minimum flows of the specific year of information to be used. At the mouth of both rivers at the Mayagüez Bay, a zero meters over mean sea level water level boundary condition was established.

Two USGS stations with continuous records of daily mean discharge data are located within the area: *50144000 Rio Grande de Añasco near San Sebastian, PR* and *50138000 Rio Guanajibo near Hormigueros, PR* (Figure 5.3.4). Daily mean discharge data for the period from January to December 2004 were obtained from the USGS on November 21, 2006 for these stations (USGS, n.d.(a); n.d.(b)). The data for the period from October 1 to December 31, 2004 were provisional subject to revision (USGS, n.d.(a); n.d.(b)) at the date it was obtained. This period was selected to be used in the preliminary runs presented in this study. Figures 5.3.5 and 5.3.6 present the 2004 daily mean discharge along with the precipitation at those locations.

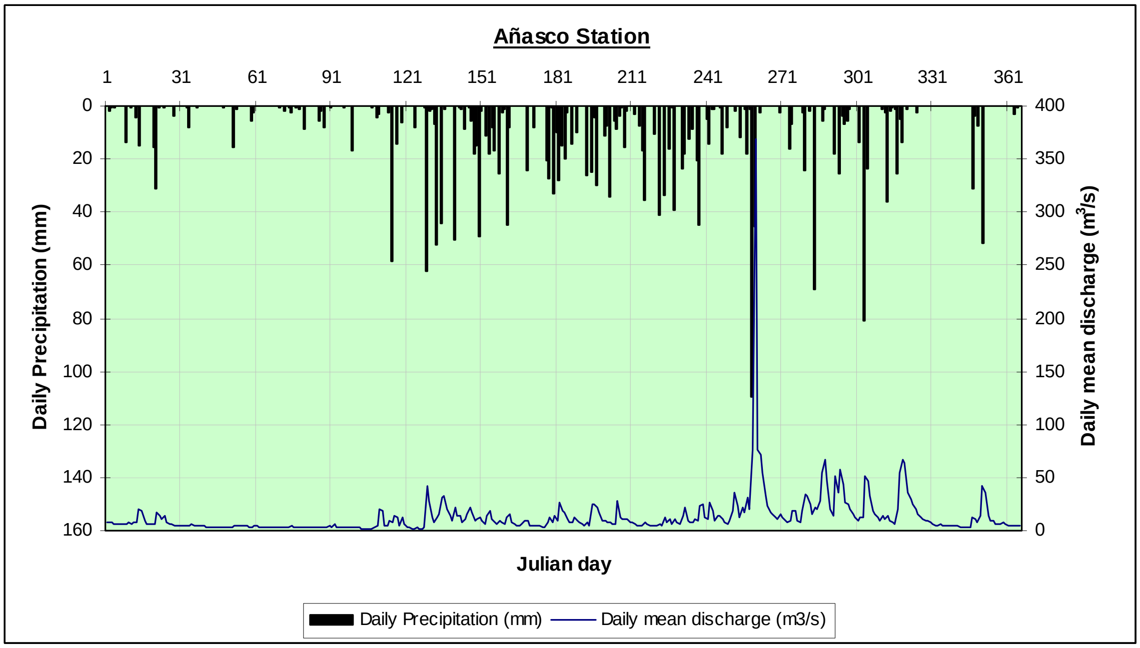


Figure 5.3.5. Daily mean discharge and precipitation for the *Rio Grande de Añasco near San Sebastian* station (USGS *50144000*).

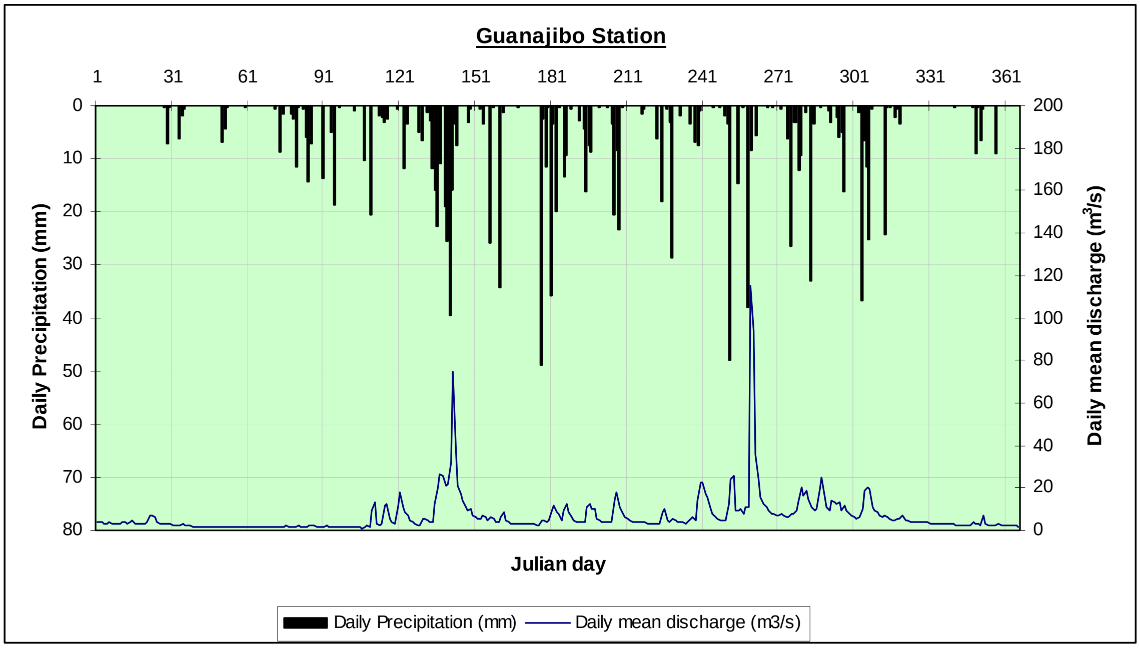


Figure 5.3.6. Daily mean discharge and precipitation for the *Rio Guanajibo near Hormigueros* station (USGS *50138000*).

For the 2004 year, the maximum daily precipitation in the Añasco flow gauging station (109.73 mm) occurred one day before of the maximum daily mean discharge which occurred on September 16 with a value of 368.12 m^3/s (Figure 5.3.5). At Guanajibo flow gauging station, the highest peak of daily mean discharge occurred on the same date as the Añasco station (September 16) with a value of 114.97 m^3/s. Although daily precipitation higher than the average for this station occurred on September 15 (38.10 mm), this was not one of the maximum rainfall values for the Guanajibo station. Therefore, it seems that the peaks of the hydrograph for this river were responding to the rainfall at other locations within the watershed more than the rainfall at this station. The three highest rainfalls that occurred during 2004 at the Guanajibo station were on June 25 (49.02 mm), September 8 (48.01 mm), and May 20 (39.62 mm) (Figure 5.3.6).

February and March are months with lowest flows; flows increase in May and decline during June for both locations (Figure 5.3.7). High values of daily mean discharge for 2004 occurred in September, October, and November for the Añasco station; and in May and

September for the Guanajibo station. Daily mean discharge was higher at the Añasco station than at Guanajibo most of the time.

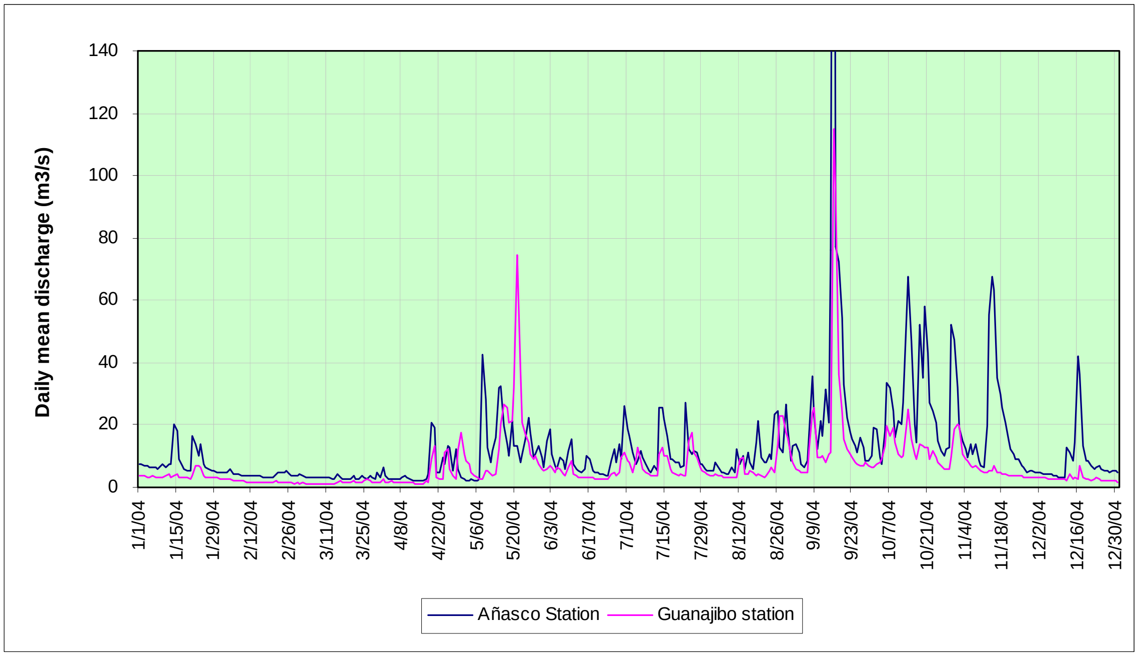


Figure 5.3.7. Daily mean discharge for the *Rio Grande de Añasco near San Sebastian* and *Rio Guanajibo near Hormigueros* stations (only shown values of daily mean discharge up to 140 m^3/s for visualization purposes).

Including the two main rivers of the study area in the model was an attempt to make the basin surface drainage process more realistic, than could have been achieved by simulating the surface runoff as overland flow for the entire study area. Also, this will permit comparisons between simulated and observed daily mean discharge values at the locations of the gauging stations for calibration and validation purposes in future studies. This will be helpful considering that the stream flow stations are conveniently located in the two main watersheds of the study area, and far away from each other).

5.3.4 River flow parameters

The parameters required by the method used to simulate rivers in the implementation of this model are the Manning's n and the leakage coefficient of the river bed material. Villalta (2004) presents Manning's n estimated values for the Añasco and Guanajibo rivers. These estimations take into account the bed and the bank roughness of each cross section (Villalta, 2004, p.75). An average of the estimated values for each one of the two rivers was proposed as initial values for the present model (Table 5.3.3). For the river bed leakage coefficient initial values were assumed based on literature reported values (Jacobsen, 1999; Madsen and Torsten, 2001; Miracapilllo, 2004; and Dahl et al., 1999), given the lack of more specific information for the study area.

Table 5.3.3. Initial values for the river flow parameters.

Parameter	Initial values	
	Añasco river	Guanajibo river
Manning's n	0.024	0.021
River bed leakage coefficient	1.00E-07	1.00E-07

5.4 EVAPOTRANSPIRATION

5.4.1 Reference ET

Estimates of reference evapotranspiration (ET_o) for the same locations of the rainfall stations were provided by Dr.Eric Harmsen (Harmsen, 2006; unpublished data). Those estimates were implemented in the numerical model with the spatial distribution of the Thiessen polygons shown in Figure 5.2.1. Daily reference evapotranspiration (ET_o) was estimated using the method of Hargreaves and Samani (1985) (Harmsen, 2006; unpublished data):

$$ET_o = 0.0023 * R_a * (T + 17.8) * (T_{max} - T_{min})^{0.5} \qquad (5.4.1)$$

Where:

ET_o : daily reference evapotranspiration

R_a : extraterrestrial radiation (mm)

T : average daily air temperature (°C)

T_{max} : average daily maximum temperature (°C)

$T_{\min}$: average daily minimum temperature (°C)

Harmsen et al. (2002) compared equation (5.4.1) with the Penman Monteith equation (Allen et al., 1998) for thirty-four locations in Puerto Rico and obtained reasonably close agreement between the two methods during many months at many locations (Figure 5.4.1). Data in red color in the Figure 5.4.1 corresponds to San German and yellow data corresponds to Mayagüez locations (locations within the study area).

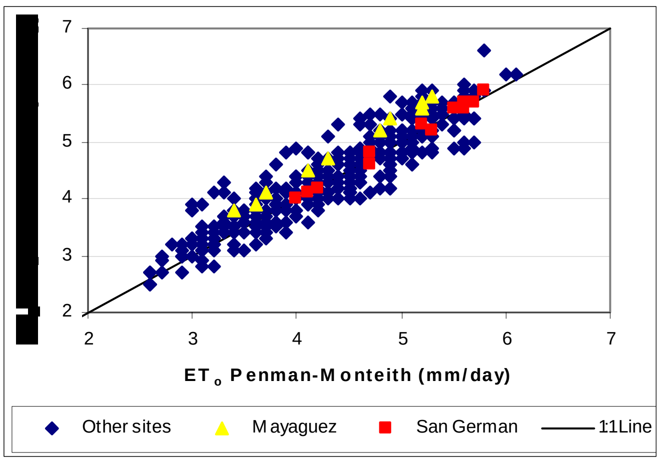


Figure 5.4.1. Comparison of long-term average daily reference evapotranspiration (ET_o) estimated by the Penman-Monteith (P-M) and Hargreaves-Samani (H-S) Methods for each month for thirty-four locations in Puerto Rico. (Harmsen et al., 2002).

The average monthly extra terrestrial radiation was obtained from the computer program PRET (Harmsen and Gonzalez, 2005). A polynomial equation was derived from the monthly data to provide daily values of extraterrestrial radiation. Daily Temperature data were obtained from the USDA Tropical Agricultural Research Station (TARS) at Mayagüez. An average temperature adjustment factor for elevation was derived from the procedure of Goyal et al. (1988) for Puerto Rico, in which the following general equation is used:

$$T = A + BZ \tag{5.4.2}$$

Where: T is temperature (°C), A and B are regression coefficients, and Z is elevation (m) above mean sea level.

An average value of B was determined from the monthly factors derived for average, minimum and maximum temperature. The new temperature adjustment factor was applied to the TARS station data to obtain average, minimum and maximum temperatures at the other eight stations located at Maricao, Río Grande de Añasco at Bo. Guacio, Río Grande de Añasco near San Sebastián, Lago Guayo at dam site near Castañer, Río Casei above Hacienda Casei, Río Guanajibo at Hwy 119, Río Guanajibo near Hormigueros, and Río Rosario near Hormigueros (Harmsen, 2006; unpublished data). The daily ET_o for the nine locations is presented in Figure 5.4.2. The results in Figure 5.4.2 indicate that the reference evapotranspiration was highest for Mayagüez (TARS) and lowest for Maricao.

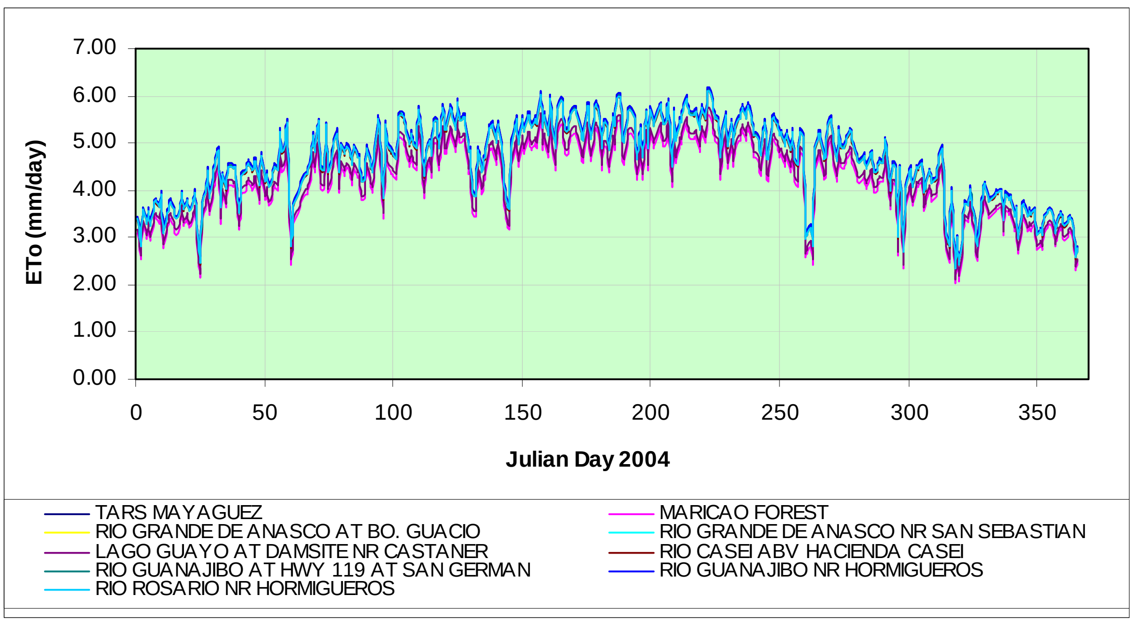


Figure 5.4.2. Reference evapotranspiration estimates at nine locations within the study area.

5.4.2 Vegetation related parameters

Three parameters needed in the computation of the actual ET and interception by the method used for preliminary runs in this study (see next chapter for details about the method proposed) are: root depth (RD), crop coefficient (K_c), and Leaf area Index (LAI). These are vegetation related parameters which vary depending on the vegetation and its stage of growth. Initial values for these parameters are proposed for each one of the land cover categories (Figure 5.3.2) and presented in Table 5.4.1. For preliminary runs of the model, the values of these parameters were assumed not to vary during the year. However, future studies could consider the variation of these parameters with time.

Table 5.4.1. Assumed initial values for RD, K_c, and LAI parameters.

Land Cover Category	Area (%)	Assumed Initial Values		
		K_c	LAI	RD (mm)
Forest, shrub, woodland and shade coffee	64.6	0.85	4.0	1,000
Pasture	21.1	0.90	1.7	1,000
Urban and barren	7.3	0.30	1.1	500
Agriculture/hay	6.7	1.00	3.6	1,000
Emergent wetlands (including seasonally flooded pasture)	0.2	1.20	6.3	1,000
Quarries, sand and rock	0.1	0.10	0.0	500

Initial proposed values of Kc for forest, shrub, woodland and shade coffee; pasture, and emergent wetlands categories were assumed taking into account some values reported in the literature (Allen et al., 1998; Thomas and Davie, 2003). A professional from the UPRM Agriculture Extension Service who works in the region was consulted to determine which are the most common crops present in the study area (personal communication, Eric Pietri (UPRM Agriculture Extension Service), August 29, 2006). According to the opinions expressed by the Agricultural Extension Agent, and after review of the available literature, an initial value of Kc was assumed for the Agriculture/hay land cover category (Table 5.4.1).

Initial values of LAI for forest, shrub, woodland and shade coffee; pasture, agriculture/hay, and emergent wetlands (including seasonally flooded pasture) land cover categories were proposed taking into account values reported in the following references: Scurlock et al. (2001), Ramírez and Jaramillo (In Press), Castillo (1997) cited by VIFINEX (2001), and Malatova (n.d.) cited by Coffee Research Institute (n.d.).

Initial root depths values were proposed taking into account values reported by Allen et al. (1998). Values for K_c, LAI, or root depth for urban and barren, and quarries, sand, and rock land cover categories were not found in the literature; initial parameter values for those categories were obtained from E. Harmsen (personal communication, August, 2006).

5.4.3 Rainfall interception

To account for rainfall interception in the numerical model, the size of the maximum amount of interception storage is determined by multiplying the interception coefficient (C_{int}) by the Leaf Area Index (LAI). C_{int} defines the maximum amount of interception storage for the vegetation. A uniform initial value of 0.05 mm was assumed for the study area which is a typical value for this parameter (DHI, 2005). Initial values for LAI were established based on the land cover categories as explained in Section 5.4.2, and presented in Table 5.4.1.

5.5 VADOSE ZONE

Soil Survey Geographic (SSURGO) databases for the Arecibo, Mayagüez, Lajas Valley, and Ponce areas (USDA, 2004a; 2004b; 2004c; 2004d) provided by the Natural Resources Conservation Service (NRCS) (Figure 5.5.1), were used in the conceptualization of the soils surface texture for the study area. Most of the study area is covered by the Soil Survey Geographic (SSURGO) database for Mayagüez Area (USDA, 2004b).

The areas shown on the soil map of the Mayagüez area are called mapping units (USDA, 1975). The surface texture for each mapping unit is presented by USDA (1995). The surface textures present in the study area, according to USDA (1995), were aggregated in to more general textures to assign initial values for the hydraulic parameters required by the method proposed to be used in the modeling of the vadoze zone (two-layer water balance method). Thus, the soils shown in Figure 5.5.1 were aggregated into six (6) categories. The soil surface texture reclassification for the study area is shown in Figure 5.5.2.

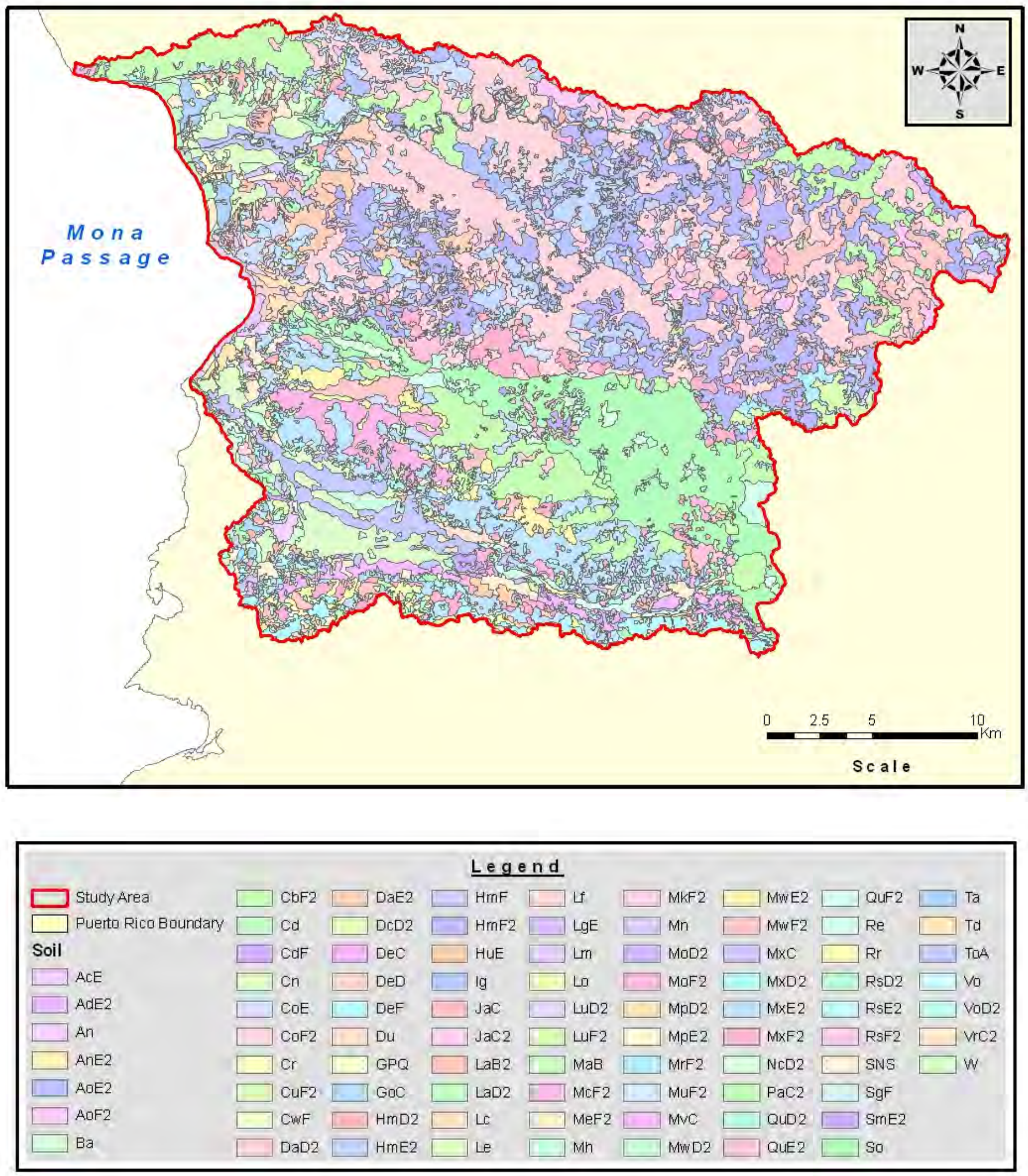


Figure 5.5.1. Soils map for the study area (Original source: USDA, 2004a; 2004b; 2004c; 2004d).

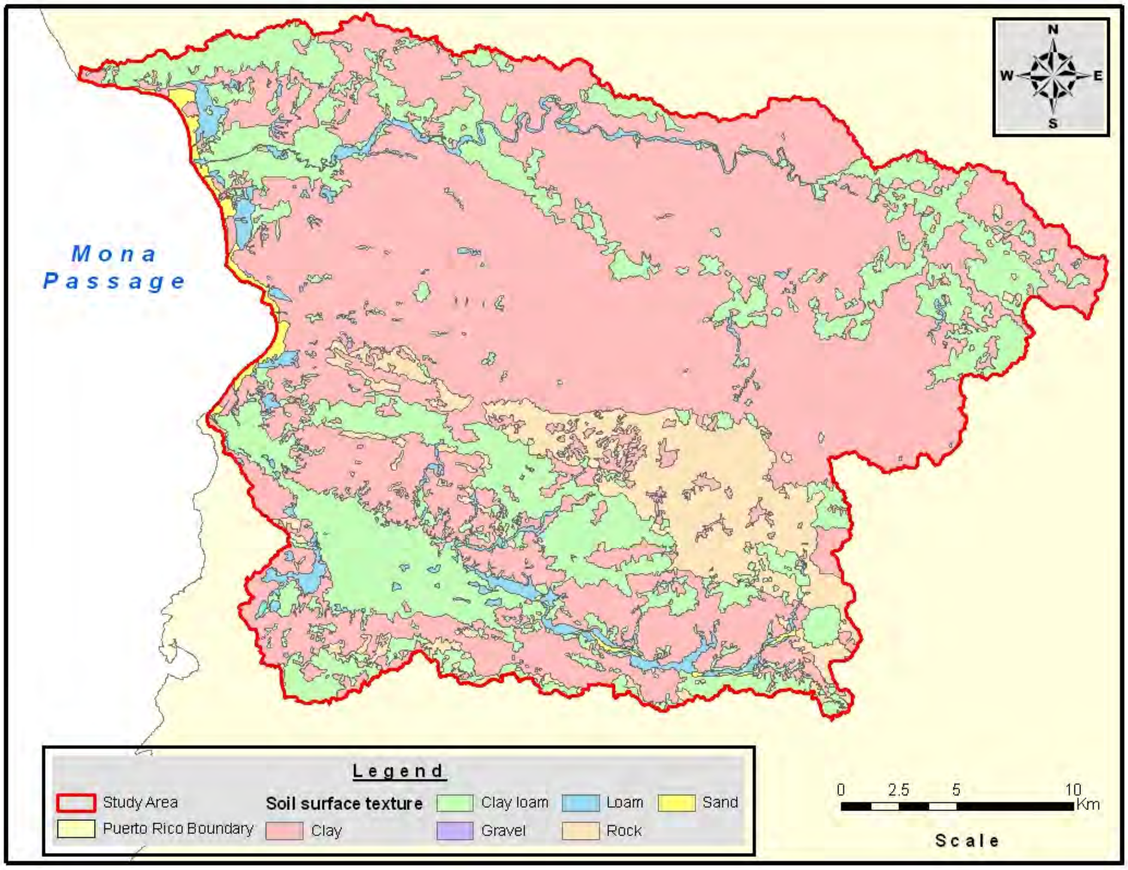


Figure 5.5.2. Soil surface texture classification for the study area.

5.5.1 Vadose zone parameters

Hydraulic parameter initial values for clay, loam, clay loam, and sand soil surface textures were assumed based on literature reported values for representative physical properties of soils by texture (Schwab et al., 1996) as shown in (Table 5.5.1). The infiltration rate equals the saturated hydraulic conductivity for the method used in the numerical model to account for the vadose zone (DHI, 2005, p.277). The spatial distribution of the soil surface texture of rock in Figure 5.5.2 seems to correspond mostly with plutonic rocks according to the generalized surficial geology of the study area shown in Figures 4.4.1 and 4.4.5, although some areas correspond with volcanic and volcaniclastic rocks. The initial value of soil water content at saturated conditions assumed for rock (0.38) is within the range of porosity values for plutonic, volcanic, and volcaniclastic rocks reported by Fetter (2001) and Freeze and Cherry (1979). The initial value of soil water content at saturated conditions for gravel was assumed equal to the rock texture given that no reported literature values were found. Range of values for hydraulic conductivity reported by Fetter (2001), Freeze and Cherry (1979), and Anderson and Woessner (1992), were considered when assigning initial values for saturated hydraulic conductivity for gravel and rock textures. Given that there were no available literature values for soil water content at field capacity and wilting point for gravel and rock soil textures, those were initially assumed equals to the sand texture.

ET surface is defined in the numerical model as the elevation of the ground surface minus the thickness of the capillarity fringe, therefore, it corresponds to the lowest elevation of the water table, such that the capillary zone still reaches the ground surface (DHI, 2005). The thickness of the capillary fringe for clay, loam, clay loam, and sand soil textures was assumed to be the height at which the water content starts to deviate substantially from the saturation in the water retention curve. The water retention curve data were obtained for generic soil textures from the numerical model Hydrus 1D using the van Genuchten equation (Simunek et al., 2005). The hydraulic retention parameters used were the default from the Hydrus database for each soil texture. For gravel and rock, the same assumed thickness as for sand was initially assumed. The initial assumed values of the thickness of the capillarity fringe are shown in Table 5.5.1.

The proposed parameter initial values are just starting point values which would be subject to adjustments during calibration efforts in future studies.

Table 5.5.1. Initial values for vadose zone hydraulic parameters.

Soil surface texture	Area (%)	Assumed Initial Values				
		Soil Water Content			Saturated Hydraulic Conductivity (m/s)	Thickness of the capillarity fringe (m)
		Saturated Conditions	Field Capacity	Wilting point		
Clay	62.49	0.53	0.44	0.21	1.39E-06	0.680
Clay loam	24.96	0.49	0.36	0.18	2.22E-06	0.215
Rock	8.69	0.38	0.15	0.07	2.66E-06	0.030
Loam	3.00	0.47	0.31	0.14	3.33E-06	0.100
Sand	0.81	0.38	0.15	0.07	1.39E-05	0.030
Gravel	0.04	0.38	0.15	0.07	1.00E-02	0.030

5.6 SATURATED ZONE

A literature review of some available hydrogeology related studies which include the study area (or part of it) was performed to gain knowledge of the different permeable geologic materials present in the study area. Also, geohydrologic and lithological well data were used to assist in the conceptualization of the different geologic layers present in the study area and its thickness (written communication, Nacer Pumps Installation Services, Inc., June 2006; written communication, Ingrid Padilla (UPRM), Feb. 2006; written communication, Jesús Rodríguez (USGS), June 2006). In addition, some GIS data provided by the USGS were processed in ArcMap to help conceptualize the aquifer system; these data include: the elevation data for Puerto Rico from the USGS National Elevation Data (NED) dataset (GRID format) and the Principal aquifers of Puerto Rico and the U.S. Virgin Islands map (Miller et al., 1997).

Once the aquifer system was conceptualized, the inputs for the proposed method for the implementation of this model were prepared. For preliminary runs of this model, the saturated flow was simulated in the numerical model using the option to solve the governing flow equation for three-dimensional saturated flow in saturated porous media. The required inputs to use this method include the spatial distribution (horizontal and vertical) of the permeable geological layers, the values of the hydraulic parameters (horizontal and vertical hydraulic conductivity, specific yield, storage coefficient, and porosity); the initial total hydraulic head; and the specification of the outer and internal boundary conditions.

According to the geographic distribution of the aquifers in Puerto Rico shown by Miller et al. (1997, p. N24) (Figure 5.6.1), the study area consists of alluvial valley aquifers (principal aquifer) and volcaniclastic-, igneous-, and sedimentary-rock aquifers (minor aquifer). According to Miller et al. (1997), the alluvial aquifers in Puerto Rico are composed by alluvial fan, alluvial valley and swamp deposits, and characteristically filled valleys incised into volcaniclastic, igneous intrusive, or limestone bedrock; whereas the volcanic-, igneous-, and sedimentary rock aquifers are composed of mostly volcaniclastic, igneous, and sedimentary rock masses intensely faulted and folded.

The literature review carried out revealed that for different areas within the basin: permeable materials vary in vertical position and thickness (Diaz and Jordan, 1987); and semiconfining/confining and permeable units are irregularly distributed and discontinuous, being their spatial distribution, extend, and thickness not well known (Rodríguez et al., 2004). Also, it is reported that the mode of occurrence of ground-water at some areas is not well understood (Rodríguez et al., 2004). According to that, and given that the present conceptual model is a first preliminary step in the development of a model intended to be used (once it is refined, calibrated and validated in future studies) to perform gross estimates of the annual water balance at a regional scale for the Mayagüez Bay drainage basin, and not to carry out a specific and/or detailed ground-water modeling, the aquifer system was conceptualized as one layer everywhere within the study area.

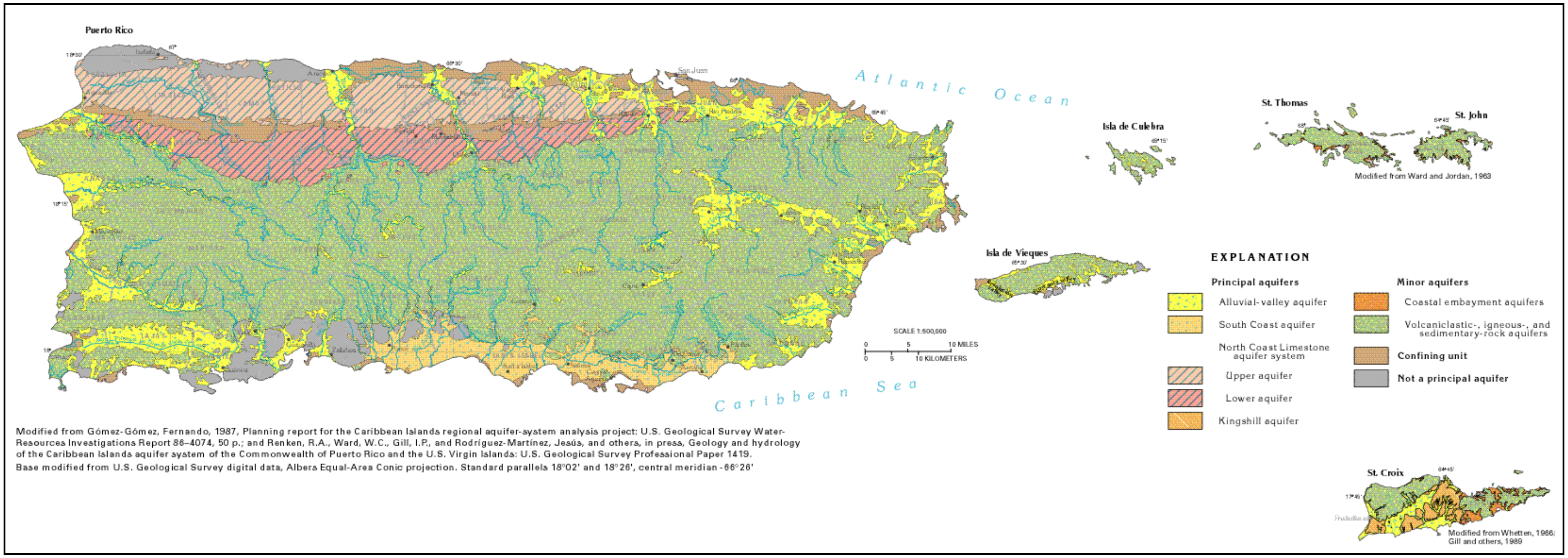


Figure 5.6.1. Geographic distribution of the aquifers in Puerto Rico and Virgin islands (Source: Miller et al., 1997 p. N24; presented with authorization from the USGS Caribbean Water Science Center).

Four geological units were conceptualized which cover the entire basin. A geologic unit in this study is understood to be a zone with uniform properties; therefore, within each one of the units, the hydraulic properties are homogenous.

Next is presented the conceptualization related to the four geologic units (Alluvial-Upper valley aquifer, Guanajibo Alluvial-Central and lower valley aquifer, Añasco Alluvial-Lower valley aquifer, and Volcaniclastic-, igneous-, and sedimentary-rock aquifer); and their thicknesses, as well as, the hydraulic parameters initial values; and boundary, and initial conditions of the model.

5.6.1 Alluvial aquifer

The delimitation of the geographic distribution of the aquifers for the study area corresponds, according to Miller et al. (1997) (Figure 5.6.1), with two alluvial valley aquifers: one corresponding with the Río Grande de Añasco and the other with the Río Guanajibo, Río Yagüez, Quebrada de Oro, and other minor streams north of the Guanajibo River. The latter will be referred in this study as the Río Guanajibo alluvial valley aquifer.

5.6.1.1 <u>Río Guanajibo alluvial valley aquifer</u>

According to Colón-Dieppa and Quiñones-Márquez (1985) and as stated in chapter 4, in the central Guanajibo valley the alluvium is underlain by limestone or directly by basalt. Ground-water occurs in sand and gravel deposits within the alluvium, in the fractured and porous limestone underlying the alluvium, and in the volcanic and other igneous rocks where they are fractured (Colón-Dieppa and Quiñones-Márquez, 1985).

Given that Colón-Dieppa and Quiñones-Márquez (1985, p.12) state that there is no limestone in the eastern part of the central Guanajibo valley, a geologic unit was defined in which no limestone is assumed to exist. This unit was delimited from the 100 ft depth contour curve of the relatively impermeable bedrock (Figure 4.4.7) upstream to the boundary of the alluvial aquifer east of the central Guanajibo alluvial valley (Figure 5.6.2); and was called Alluvial-Upper valley aquifer.

The presence of limestone in areas north to the central Guanajibo valley in the Yagüez and Coastal watersheds has been indicated by lithologic log data for Pozo Hermanos Arbona, Pozo Sábalo #2, and Pozo Rivera wells (written communication, Jesús Rodríguez (USGS), June 2006), as well as for the Clínica Dr.Perea well (Rodríguez et al., 2004). Given the similarity in the subsurface materials described for the central Guanajibo valley and the MayHT1 hydrogeologic terrain (presence of alluvium underline by limestone and other rocks; and being that the limestone is the most important water-bearing unit in the lower zones); for the purpose of this study a geologic unit in which limestone is present was defined downstream of the Alluvial-Upper valley aquifer unit, covering the remaining area of the Río Guanajibo alluvial valley aquifer (Figures 5.6.2). This unit was called Guanajibo Alluvial-Central and lower valley aquifer.

Thus, two geologic units were conceptualized for the Río Guanajibo alluvial valley aquifer (Figure 5.6.2):

- Guanajibo Alluvial-Central and lower valley aquifer: composed by alluvium underlain by limestone, which in turn is underlain by fracture rock.
- Alluvial-Upper valley aquifer: composed by alluvium underlain by fractured rock.

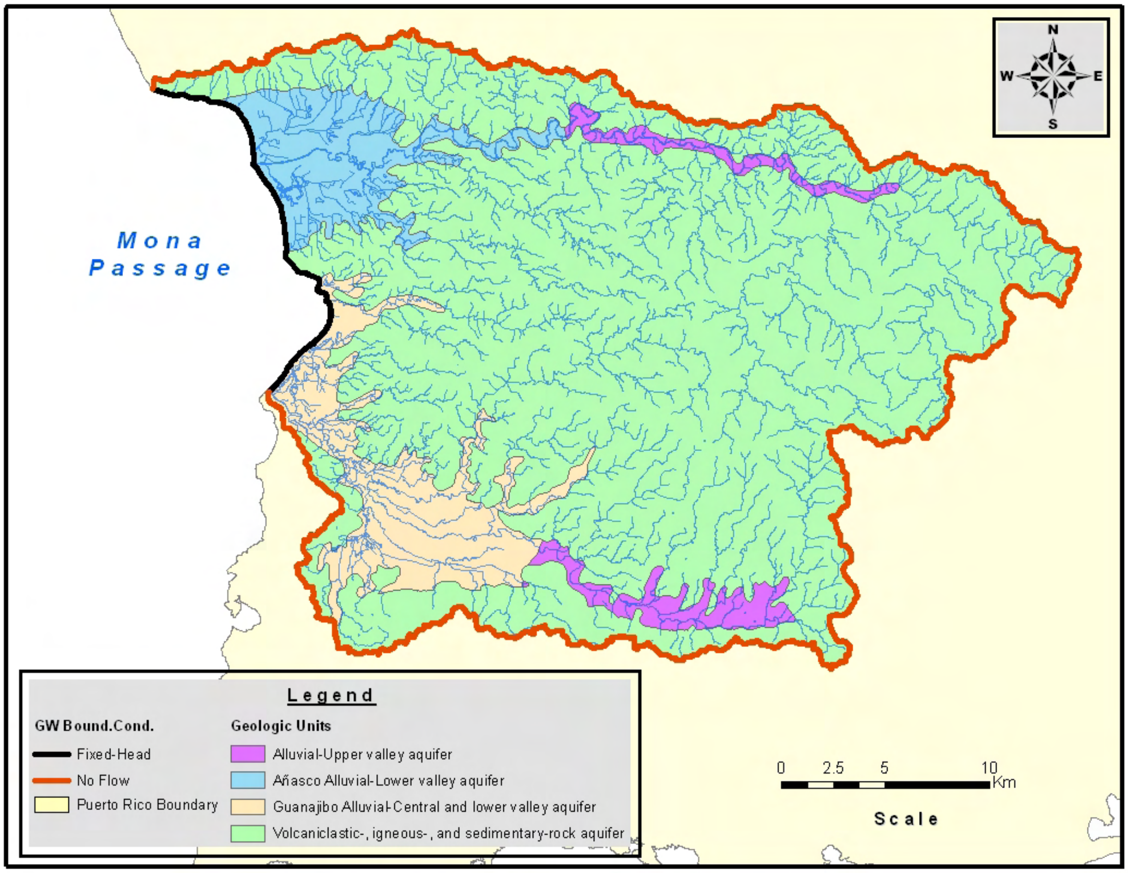


Figure 5.6.2. Conceptualization of the geologic units spatial distribution and ground-water boundaries.

5.6.1.2 <u>Río Grande de Añasco alluvial valley aquifer</u>

According to Díaz and Jordan (1987) and as stated in chapter 4, four subsurface zones of materials can be differentiated in the lower Añasco valley: soil and alluvium above the water table (upper most zone), saturated alluvium (zone II), layers of hard dense clay and soft limestone (zone III), and rocks of predominately igneous origin (zone IV) (Figure 4.4.3). The principal water yielding zones are the layers of sand and gravel within the alluvium and the limestone of zone III (Díaz and Jordan, 1987).

Díaz and Jordan (1987) have reported that zone III underlies the alluvium throughout the lower valley, and also, it is possible that it underlies the valley upstream of Josefa for a distance of several miles. Based on what was previously stated, a geologic unit was defined from several miles upstream of Josefa toward the east to the boundary of the alluvial aquifer east of the lower Añasco alluvial valley in which limestone was assumed not to be present. Another unit was defined downstream of the previous one towards the west extending to the coast, in which limestone is present. This unit was called the Añasco Alluvial-Lower valley aquifer (Figure 5.6.2).

Given the similarities in the permeable materials assumed to exist in the two units located in the upper parts of the Añasco and Guanajibo valleys, those were assumed to have the same properties, and therefore, was defined as one geologic unit which was called Alluvial-Upper valley aquifer.

For the purposes of this study a fractured rock layer is assumed to underlie zone III in the lower valley and the alluvium in the upper Añasco aquifer valley.

Thus, two geologic units were conceptualized for the Río Añasco alluvial valley aquifer (Figure 5.6.2):

- Añasco Alluvial-Lower valley aquifer: composed by alluvium underlain by layers of hard clay and soft limestone, which in turn are underlain by fracture rock.
- Alluvial-Upper valley aquifer: composed by alluvium underlain by fractured rock.

Thickness of the aquifer had to be estimated to model the ground-water system. This was a challenging task in this study given the lack of information and uncertainty about the distribution of the permeable materials over the study area and their thickness. Therefore, the estimation of the aquifer thickness in this study represents a preliminary attempt to accomplish a gross conceptualization of the aquifer system based on numerous assumptions, to accomplish a regional integrated hydrologic modeling; and consequently, is not intended to be a model for small-scale or specific ground-water studies. The entire conceptualization of the aquifer system of the study area as explained in this study is entirely subject to be improved in future studies, as more data is available, or there is a better understanding of the ground-water system in the area.

The three geologic units defined for the alluvial valley aquifers were assumed to have a fracture rock permeable layer underlying the other permeable materials. An gross preliminary estimate of 60 m was assumed for the thickness of that layer for the Guanajibo Alluvial-Central and lower valley aquifer geologic unit; based on available information of two wells located in the central Guanajibo Valley (PRDOA No.2 and PRDOA No.3; Colón-Dieppa and Quiñones-Márquez, 1985); and the generalized depth to relatively impermeable bedrock in the central Guanjibo valley presented by Colón-Dieppa and Quiñones-Márquez (1985). As no data was found relative to the fractured rock thickness for the lower Añasco valley; the thickness of this layer in the Añasco Alluvial-Lower valley aquifer geologic unit was assumed to be the same as assumed in the Guanajibo Alluvial-Central and lower valley aquifer geologic unit. This assumption was made given the similar geology presented in both Guanajibo and Añasco valleys (Renken et al., 2002), and because the thickness of this layer for the area of the Añasco alluvial aquifer is not expected to have a significant influence on the estimation of the regional annual water balance. However, this assumption has to be verified by future studies when there is a better understanding of this aquifer system or there is new available data about the thickness of the permeable layers in the area.

The contours of the estimated depth to relatively impermeable bedrock through the central Guanajibo valley presented by Colón-Dieppa and Quiñones-Márquez (1985) (Figure 4.4.7), were used to assist in the spatial interpolation of the permeable material thickness for the geologic units: Guanajibo Alluvial-Central and lower valley aquifer, Añasco Alluvial-Lower valley aquifer, and Alluvial-Upper valley aquifer (Figure 5.6.2). To perform that interpolation, data from the subsurface materials cross sections located in the Río Grande de Añasco lower valley shown in Figure 4.4.3 were used. Cross sections B-B', C-C', D-D' and E-E' in Figure 4.4.3 show the location of the rock underlying the hard clay and soft limestone layer. To the bottom of the hard clay and soft limestone layer were added the assumed 60 m thickness of the fracture rock, and the resulting depth was assumed to be the bottom of the permeable materials along those cross sections. In the case of cross section A-A', as the depth of the bottom of the hard clay and soft limestone layer was not reached, the assumed 60 m thickness of the permeable rock were added to the maximum depth reached by the cross section, and the resulting depth was assumed as the bottom of the permeable materials for that location. The location of the cross sections and the contours of the estimated depth to relatively impermeable bedrock through the central Guanajibo valley (Figure 4.4.7) were georeferenced to the same coordinate system in the GIS, and used to perform an interpolation in ArcMap to estimate the thickness of the permeable materials over the area of the three geologic units described previously. Additional assumptions made to perform the interpolation included:

- Along the boundary of the geologic units: Añasco Alluvial-Lower valley aquifer and Alluvial-Upper valley aquifer (Figure 5.6.2), the thickness of the permeable materials was assumed as 60 m (assumed thickness of the fractured rock present in these geologic units).
- Given that no information was found regarding the depth to the relative impermeable bedrock in the northern and western areas of the Guanajibo Alluvial-Central and lower valley aquifer geologic unit (from the mouth of the Guanajibo River to the Quebrada de Oro valley), a permeable material thickness of 90 m was assumed along the coast in this geologic unit. This thickness was assumed greater than the assumed thickness of the fractured bedrock layer to account for the presence of the other permeable materials.
- Along the boundary of the alluvial-Upper valley aquifer geologic unit of the Guanajibo valley, the thickness of the aquifer was assumed to be 30 m, based on the most eastern contour curve of the depth to relatively impermeable bedrock presented by Colón-Dieppa and Quiñones-Márquez (1985) (Figure 4.4.7).

Once the interpolation to estimate the thickness of the permeable materials for the geologic units described above was performed, the resulting map was subtracted from the land elevation to obtain an estimate of the elevation of the relatively impermeable bedrock in those areas. The resulting raster format map was converted to contours to be input into the numerical model. The depth to the relatively impermeable bedrock map was checked with well log data provided by the USGS Caribbean Water Science Center (written communication, Jesús Rodríguez (USGS), June 2006) (Table 5.6.1). The depth to the relatively impermeable bedrock was verified to be deeper than the depth at which water or decomposed rock was encountered during the construction of the eight wells presented in Table 5.6.1.

Table 5.6.1. Well geohydrologic data and assumed depth to relatively impermeable bedrock according to the conceptualization.

USGS STATION NAME	WELL GEOHYDROLOGIC DATA		ASSUMED DEPTH TO RELATIVELY IMPERMEABLE BEDROCK (m)*	SUPERFICIAL WATERSHED LOCATION
	Depth (m)	Description		
Hormigueros well	28.00 - 32.30	Yellow Limestone with shells (water)	64.5	Guanajibo
C.C Rum Dist. #01 well	12.20 - 13.40	Blue caving sand, water	78.5	Guanajibo
Pozo Nadal # 02	50.00 - 53.30	Yellow sand and silt (water)	87.5	Coastal / Yaguez watershed
Pozo Rochelaise # 02	36.6 - 41.1	Yellow descomposed rock	77.5	Coastal / Yaguez watershed
Pozo Rivera	37.80 - 46.33	Yellow soft tosca (water)	88.0	Coastal / Yaguez watershed
Pozo Rochelaise # 03	9.5 - 37.6	Gray rock with layers of clay (water)	77.5	Coastal / Yaguez watershed
Pozo Rochelaise # 06	14.6	Water level	79.5	Coastal / Yaguez watershed
Pozo Hnos Arbona	13.4	Water level	84.0	Coastal / Yaguez watershed

*According with the conceptualization

5.6.2 Volcaniclastic-, igneous-, and sedimentary-rock aquifer

The remaining part of the study area corresponds geographically, according to the distribution of aquifers presented in the Ground-Water Atlas of the United States (Miller et al., 1997), with a minor aquifer which consists of the upper 15 m to a maximum of about 90 m of fractured and weathered volcaniclastic, plutonic and sedimentary rocks that composes the core of Puerto Rico and the U.S. Virgin Islands (Miller et al., 1997). According to Miller et al. (1997), the permeability of this aquifer has been developed as a result of weathering, faulting and fracturing of the rocks masses.

No information was found in the literature about the thickness of this unit for the study area. Therefore, well log information was requested from a company which has drilled wells in the study area, and the well construction reports provided were used to assume a thickness for this aquifer. According with that information, water has been encountered at depths of 107 m and 113 m at wells drilled within the study area in the geologic unit corresponding with the rock aquifer (written communication, Nacer Pumps Installation Services, Inc., June 2006). Based on that information, for the purpose of this study an assumed value of 120 m was conceptualized as the thickness of the permeable materials for this geologic unit. There is much uncertainty associated with this assumption, given the lack of data about the thickness of this aquifer and its great extend over the study area. The assumption made is one of the limitations of this conceptual model and has to be verified by future studies as more data becomes available, or there is a better understanding of the vertical distribution of the fractured rock layer for the area.

According to the available lithologic information of wells drilled in the study area (written communication, Ingrid Padilla, Feb. 2006; written communication, Nacer Pumps Installation Services, Inc., June 2006) and the experience of a driller in the area (personal communication, Manuel Franco, July 2006), the subsurface materials present in the area corresponding with the aerial extent of the volcaniclastic-, igneous-, and sedimentary-rock aquifer shown by Miller et al., (1997) in the study area; are usually described as a layer of clay underlain by fractured and weathered rock.

The assumed fractured rock thickness of this geologic unit was subtracted from the land surface elevation to obtain an estimation of the elevation of the bottom of the bedrock aquifer. This procedure was performed in ArcMap.

Average thickness of the permeable materials conceptualized to compose each one of the geologic units described above were assumed for the purpose of estimating initial “effective” (or equivalent) values for horizontal and vertical hydraulic conductivity. That is, the hydrologic properties were weight averaged based on the layer thicknesses to obtain the effective value of the property. This calculation assumed that the permeable materials are in layers over the total extend within each one of the geologic units, and their thickness is constant. This is not true in nature; permeable materials do not extend continuously horizontally within the geologic units, and do not have a constant thickness everywhere. However, these assumptions were made in order to obtain a rough approximation of gross realistic values of the effective hydraulic conductivities. The thickness of the permeable materials was assumed based on the following rationale:

- Guanajibo Alluvial-Central and lower valley aquifer geologic unit. This unit was assumed to be composed of alluvium underlain by limestone, which in turn is underlain by fracture rock. According with Veve and Taggart (1996), the alluvium in the central Guanajibo valley is about 21.3 m (70 ft) in thickness. Northward of that, in the Mayagüez municipality, the alluvium can reach 30.5 m (100 ft) thinning towards the rock outcrops (Rodríguez et al., 2004). A value of 21 m was assumed as the thickness of the alluvium for this unit. Data of five wells located in this geologic unit (Teresa #02, C.C Rum.Dist. #01 well, C.C Rum.Dist. #03 well, Written communication, Jesús Rodríguez, June 2006; PRASA No3, PRDOA No.2, Colón-Dieppa and Quiñones-Márquez, 1985, p. 13) were compared with the depths to the relatively impermeable bedrock (according with the conceptualization). Depth where the rock starts to be present in the wells logs were subtracted from the conceptualized depth to the relatively impermeable bedrock to obtain an estimate of the thickness of the permeable bedrock. An average value for the five wells was 59.6 m, therefore the assumed thickness of the fracture bedrock for this unit was assumed to be 60 m. An average value of the thickness for this geologic unit was computed with ArcGIS and the assumed values for alluvium and fracture rock were subtracted from it, to estimate an assumed value for limestone thickness (4 m).
- Añasco Alluvial-Lower valley aquifer. This geologic unit was conceptualized to be composed by alluvium underlain by layers of hard clay and soft limestone, which in turn are underlain by fracture rock. According to Díaz and Jordan (1987), saturated alluvium generally ranges in thickness from 15.24 to 30.5 m (50 to 100 ft) in the central part of the Añasco valley; thinning to a featheredge at the bedrock boundaries. Therefore, the assumed thickness of this material was 11 m.

Given the lack of data for this unit about the fractured rock thickness, it was assumed to be the same as the Guanajibo Alluvial-Central and lower valley aquifer geologic unit (60 m). An average value of the thickness for this geologic unit was computed with ArcGIS and the assumed values for alluvium and fracture rock were subtracted from it, to estimate an assumed value for hard clay and soft limestone layer thickness (28 m).

- Alluvial-Upper valley aquifer. This geologic unit was conceptualized to be composed by alluvium underlain by fractured rock. An average of the assumed thicknesses of the alluvium material in the two previous geologic units was assumed to be the thickness of the alluvium layer for this unit (16 m). For the fracture rock layer, the assumed thickness was 29 m. This value was assumed taking into account an average of the differences of the total thickness minus the alluvium material thickness for the two previous geologic units.
- Volcaniclastic-, igneous-, and sedimentary-rock aquifer. This geologic unit was conceptualized to be composed by a layer of clay underlain by fractured and weathered rock. An average thickness of the clay layer for this unit was assumed to be 17 m, based on well log information (written communication, Nacer Pumps Installation Services, Inc., 8 June 2006; written communication, Ingrid Padilla, Feb. 2006). The thickness of the fractured and weathered rock layer of this aquifer was the difference between the total unit and the clay layer assumed thicknesses, being 103 m.

The proposed initial values for the hydraulic parameters of the different geologic units (Table 5.6.2.) were estimated taking into account ranges of values reported in the literature for the different materials (Anderson and Woessner, 1992; Fetter, 2001; Freeze and Cherry, 1979).

Díaz and Jordan (1987, p. 30) reported an estimated transmissivity value of 2.31 X 10^{-3} m^2/s (2,150 ft^2/d) from a pumping test performed on well 7 which penetrated 15.24 m (50 ft) of limestone in the lower Añasco valley (Figure 4.4.2). The location of the well corresponds to the Añasco Alluvial-Lower valley aquifer geological unit of the study area. According to the transmissivity value and thickness of the limestone value reported, the estimated hydraulic conductivity would be equal to 1.51 X 10^{-4} m/s. This value is very close to the one assumed for this unit according to the conceptualization (2.14 X 10^{-4} m/s).

Table 5.6.2. Ground-water flow hydraulic parameters initial assumed values.

Hydrogeologic unit	PARAMETERS - Initial assumed values				
	K_{Hor} (m/s)	K_{Ver} (m/s)	S_y ()	S_s (m^{-1})	n ()
Volcaniclastic-, igneous-, and sedimentary-rock aquifer	2.92E-07	6.05E-10	9.00E-02	2.54E-04	0.41
Guanajibo Alluvial-Central and lower valley aquifer	4.75E-04	4.67E-10	2.30E-01	8.93E-05	0.34
Añasco Alluvial-Lower valley aquifer	2.14E-04	3.02E-10	2.30E-01	2.30E-04	0.37
Alluvial-Upper valley aquifer	6.84E-04	3.25E-10	2.30E-01	2.17E-04	0.38

K_{hor}: Horizontal hydraulic conductivity
K_{ver}: Vertical hydraulic conductivity
$S_{y:}$ Specific yield
S_s: Specific storage
n: Porosity

Rodríguez (1996) reported horizontal hydraulic conductivities in the range from 3.52 X 10^{-5} m/s (10 ft/day) to 7.05 X 10^{-4} m/s (200 ft/day) for the water table aquifer located in the Bajura area (North of Cabo Rojo town). The Bajura area corresponds to the Guanajibo Alluvial-Central and lower valley aquifer geologic unit of the study area. The initially assumed value of hydraulic conductivity for this geologic unit (4.75 X 10^{-4} m/s) is in the range of values reported by Rodríguez (1996).

5.6.3 Boundary conditions

Two ground-water boundary conditions were specified along the boundaries of the study area (Figure 5.6.2). At the west part of the study area along the coast, it was assumed a constant head boundary of zero meters over mean sea level (Dirichlet condition). For the remaining limit of the study area it was assumed no flow ground-water boundary condition (Newmann condition) corresponding with the surface water divide (i.e. boundary of the surface basin shown in Figure 4.1.2). The assumption of the no-flow ground-water boundary condition may not be appropriate at the location of the dams of the lakes Guayo, Yahuecas, and Prieto. However, the length of these dams is small relative to the overall length of the drainage basin boundary. This assumption constitutes one limitation of the model and should be verified in future studies. Given the lack of enough spatially distributed ground-water head data over the study area, the initial conditions were assumed to be at the ground surface for the first preliminary run.

5.6.4 Ground-water withdrawals

Ground-water withdrawals were not included in the model because a significant portion of water extracted from the aquifers is likely returned either to the ground-water (via septic systems) or to rivers (via wastewater treatment facilities), and these "internal" flows are not expected to have significant effect in the regional water budget, which is only concerned with water entering or leaving across boundaries. Furthermore, the groundwater withdrawals could not represent a significant percentage of the water budget as shown below.

Ground-water withdrawals by aquifer data for the year 2005 were provided by the USGS (personal communication, Wanda Molina (USGS), May 7, 2007, provisional data subject to revision). The estimated withdrawals for the Rio Grande de Añasco Valley Alluvial Aquifer, Rio Yagüez Valley Alluvial Aquifer, Lajas Valley, Interior Provinces - San Sebastian Formation, and Rio Guanajibo Valley Aquifer are presented in Table 5.6.3. Total withdrawals for the municipalities which are totally or partially included within the study area (red font color in Table 5.6.3) totaled 12 Mgal/day (Million of gallons per day). Assuming this rate during each day in the 2005 year (365 days) gives a total of 4,380 Mgal/year = 16,580,103.61 m^3/year. This value represents only 1.06% of the total precipitation for the study area during the year 2004 (according to the assumed rainfall spatial distribution and filling data process performed in this study, Table 5.2.2) as can be see from the following calculation.

$$\frac{16{,}580{,}103.61\dfrac{m^3}{year}}{1{,}567{,}922{,}641.03\dfrac{m^3}{year}} = 0.0106 = 1.06\%$$

Table 5.6.3. Estimated ground-water withdrawals for some aquifers for the year 2005 (personal communication, Wanda Molina (USGS), May 7, 2007, provisional data subject to revision). Red lettering indicates municipalities located within or partly within the study area.

Aquifer	Total Withdrawals (Mgal/day)	Irrigation (Mgal/day)	Public Supply (Mgal/day)*	Domestic self-supplied (Mgal/day)	Industrial (Mgal/day)	Thermoelectric (Mgal/day)
Interior Provinces - San Sebastian Formation						
Adjuntas	0.29	0.09	0.16	0.04		
Aguas Buenas	0.79	0.03	0.71	0.05		
Aibonito	1.56	0.01	1.29	0.02	0.24	
Barranquitas	2.14	0.04	2.02	0.08		
Ciales	0.05	0.02	0.02	0.01		
Coamo	0.23	0.05	0.17	0.01		
Comerio	0.36	0	0.32	0.04		
Corozal	0.63	0.08	0.45	0.10		
Guaynabo	0.22	0.21	0.00	0.01		
Jayuya	0.14	0.08	0.00	0.06		
Lares	0.12	0.04	0.06	0.02		
Las Marias	0.02	0.02	0.00	0.00		
Las Piedras	0.34	0.06	0.19	0.03	0.06	
Loiza	0.05	0.05	0.00	0.00		
Maricao	0.10	0.03	0.00	0.00	0.07	
Naranjito	0.45	0.01	0.36	0.08		
Orocovis	0.33	0.09	0.19	0.05		
San Lorenzo	0.41	0.14	0.20	0.06	0.01	
San Sebastian	0.46	0.27	0.18	0.01		
Trujillo Alto	0.01	0	0.00	0.01		
Utuado	0.23	0.02	0.16	0.05		
Villalba	0.22	0.06	0.12	0.04		
Lajas Valley						
Cabo Rojo	5.28	0.45	4.83	0		
Lajas	3.21	2.76	0.44	0.01		
Sabana Grande	0.03	0.00	0.03	0.00		
San German	1.71	0.01	1.68	0.02		
Rio Gde Añasco Valley Alluvial Aquifer						
Añasco	0.56	0.02	0.53	0.01		
Rincón	1.27	0.02	1.24	0.01		
Rio Guanajibo Valley Aquifer						
Hormigueros	0.92	0.07	0.85	0		
Rio Yagüez Valley Alluvial Aquifer						
Mayagüez	1.24	0.08	1.14	0.02		

*Public supply includes the PRASA and Non-PRASA systems.

6 NUMERICAL MODEL SET UP AND PRELIMINARY RUNS

6.1 NUMERICAL MODEL DESCRIPTION

Mike She / Mike 11 (DHI, 2004a, 2004b, and 2005) is a deterministic, physically-based, spatially-distributed, finite difference, modeling system. Mike She is capable of modeling interception, evapotranspiration, overland flow, unsaturated zone flow, and ground-water flow. Mike 11 is a numerical model for rivers and channels, with a hydrodynamic module capable of computing unsteady flows in rivers (DHI, 2004a). The components of Mike She are coupled with Mike 11 (DHI, 2005). A general description of this modeling system was given in the Chapter 2. The following is a brief overview of the methods used in the model to perform the preliminary runs presented in this chapter (numerous other capabilities of the numerical model are not included here, as for example solute transport capabilities). However, future refinements and improvements of the model may want to use other methods available in the numeric models. More details about the numeric models can be found in the references: DHI, 2004a, 2004b, and 2005. The methodologies explained below are based on information (in some cases verbatim) provided by DHI (DHI, 2004a; 2004b; 2005; written communication, Douglas Graham (DHI), April 18, 2007; written communication, María Loinaz (DHI), April 12, 2007).

6.1.1 Overland flow

Two methods are available in Mike She to simulate overland flow: the diffusive wave approximation of the Saint Venant equations, and a semi-distributed approach based on the Manning's equation (DHI, 2005). The first approach was used for the preliminary runs in this study. In Mike She when the diffusive wave approximation is selected, a finite difference method is used to solve the overland flow equations (DHI, 2005).

6.1.2 River/channel flow

In this study the main channel of the Añasco and Guanajibo rivers were simulated in the numerical model Mike 11. Mike 11 provides three flow descriptions: dynamic wave, diffusive wave, and kinematic wave approaches (DHI, 2004a). A finite different scheme is used to solve the equations. A computational grid is generated automatically by the numerical model consisting in alternating *Q*- and *h*-points (i.e. points where the discharge *Q*, and water level *h*, are computed respectively at each time step) (DHI, 2004a). For the last preliminary run presented in this study (see next chapter) the higher order fully dynamic approach was used.

On the edge that separates adjacent grid cells of the numeric model Mike She, there are located *river links* which account for the coupling between Mike She and Mike 11 (DHI, 2005). The user can specified *coupling reaches*, which are the segments of the river(s) where exchange of water occurs. The coordinates of the digitized points and H-points of the Mike 11 model on the coupling reaches determine the location of the river links (DHI, 2005). The river network can be reproduced more accurately when the Mike She grid is more refined (i.e., smaller the grid cell size is used) (DHI, 2005).

River-aquifer exchange computations are calculated using a simplified triangular cross section; whose dimensions are based on the river bank width, the highest bank elevation, and deepest bed elevation (DHI, 2005). The cross sections input into Mike 11 are used to interpolate the cross sections for the river links; and the water levels at the Mike She river links are interpolated from the Mike 11 H-points water levels (DHI, 2005). The river-aquifer exchange flow is computed by (when the grid cell size is larger than the river width) (DHI, 2005):

$$Q_i = \Delta h_i C_i \qquad (6.1.2.1)$$

Where:

Q : exchange flow between a saturated zone grid cell and the river link

Δh : head difference between the river and the grid cell

C : conductance

i : subscript which refers to either of the two cells adjacent to the river link.

Three options are available in Mike She to compute the conductance C between the cell and the river link depending on if the flow resistance is assumed to be based on the aquifer material only (called full contact), the riverbed material only (reduced contact (b)), or both the aquifer and the riverbed material (reduced contact (a)) (DHI, 2005). For the preliminary runs presented in this study, the last option was used. In this case there is a head loss across the river bed lining and another due to the aquifer material. The equation used to compute conductance in this case is (DHI, 2005):

$$C_i = \frac{1}{\dfrac{ds}{K_i * da_i * dx} + \dfrac{1}{L_{c_i} * w_i * dx}} \tag{6.1.2.2}$$

Where:

K_i : horizontal conductivity in the grid cell

ds : average flow length (assumed to be the distance from the grid node to the middle of the river bank in the simplified cross section)

da : maximum vertical surface available for exchange flow

dx : grid size used in the saturated zone component

L_{c_i} : leakage coefficient (1/time) of the bed material

w_i : wetted perimeter of the cross section

Two options available in Mike She to deal with flood areas are: no flooding and manual flood area. In the first option, the exchange between the river and overland flow is only from overland flow to the river (DHI, 2005). The water in the river is allowed to rise above the Mike She adjacent cells without flooding them (DHI, 2005). The manual flood area option allows the user to specify areas that can be flooded (DHI, 2005). For the preliminary runs presented in this study, the no flooding approach was used.

6.1.3 Evapotranspiration and Unsaturated Zone

For the preliminary runs of the model in this study, the use of a method available in Mike She called the Two-Layer Water Balance was used. According to DHI (2005), this method is particularly useful for areas with shallow ground-water table. However, it may be possible to calibrate the parameters in order for the model to perform well under most conditions (DHI, 2005; written communication, Maria Loinaz (DHI), April 12, 2007). The computation of recharge to the saturated zone and actual ET are the main objective of this method (DHI, 2005).

The model does not represent the water retention curve (pressure vs. moisture content), and it does not account for the relation between soil moisture content and unsaturated hydraulic conductivity, and therefore constitute potential model limitations (DHI, 2005; Maria Loinaz (DHI), April 12, 2007). The vadose zone is considered to be composed of two layers representing average moisture conditions (DHI, 2005). Parameters required by this method include properties of the soil (constant infiltration capacity, soil moisture content at: saturation, wilting point, and field capacity), and features of the vegetation (LAI and Root depth).

6.1.3.1 Interception

Interception is simulated as an interception storage, having a maximum amount ($S_{\text{int max}}$) which depends on the LAI (written communication, Douglas Graham (DHI), April 18, 2007). Thus:

$$S_{\text{int max}} = C_{\text{int}} * LAI \tag{6.1.3.1}$$

where C_{int} is defined as the interception storage capacity.

When $S_{\text{int max}}$ is exceeded, the excess water is added to the ponded water on the ground surface (written communication, Douglas Graham (DHI), April 18, 2007).

6.1.3.2 Infiltration

The infiltration to the upper UZ layer is limited by the depth of ponded water (amount of available water for infiltration), the rate of infiltration, and the estimated amount of water that would raise the water table to the ground surface (written communication, Douglas Graham (DHI), April 18, 2007).

6.1.3.3 Soil moisture and recharge to the saturated zone

A term related with the soil moisture estimation in this method is the ET extinction depth. It is defined as the depth of the root zone plus the thickness of the capillary fringe. The two layers representing the vadose zone in this method are an upper and a lower layer. The upper layer extends from the ground surface to the ET extinction depth. ET is only allowed from this layer. The lower layer is added if the water table is below the ET extinction depth. This layer extends from the bottom of the upper layer to the water table (written communication, Douglas Graham (DHI), April 18, 2007).

The average moisture content of the upper layer varies between two values (maximum water content ($\theta_{\max}$) and the minimum water content ($\theta_{\min}$)). These values which decrease linearly with the depth to the water table. When the actual moisture content equals $\theta_{\max}$, vertical infiltration to the lower UZ layer occurs. The moisture content of the lower layer varies from the wilting point to the field capacity, and recharge to ground-water occurs when the water content equals or exceeds the field capacity during a time step (written communication, Douglas Graham (DHI), April 18, 2007).

6.1.3.4 Evapotranspiration

The maximum amount of evapotranspiration ($ET_{\max}$) that can be removed in one time step is defined as (written communication, Douglas Graham (DHI), April 18, 2007):

$$ET_{\max} = ET_{rate} * \Delta t \qquad (6.1.3.2)$$

where $ET_{rate} = ET_c = ET_o * K_c$

Evapotranspiration is removed in the following order: ET from snow storage (until $ET_{\max}$ is satisfied or snow storage is exhausted); ET from interception storage (until $ET_{\max}$ is satisfied or interception storage is exhausted); ET from ponded water (until $ET_{\max}$ is satisfied or ponded water is exhausted), ET from unsaturated zone (until $ET_{\max}$ is satisfied or the average water content in the upper UZ layer is reduced to $\theta_{\min}$); and ET from the saturated zone (if the water table is above the extinction depth). The actual evapotranspiration is computed as the sum of those contributions (written communication, Douglas Graham (DHI), April 18, 2007). The detail of the computations for each contribution is not shown here.

6.1.4 Saturated flow

Two approaches are available in Mike She to account for saturated flow: a three dimensional finite difference and a linear reservoir method. For preliminary runs presented in this study, the finite difference approach is used. In this method the governing flow equation for three dimensional saturated flow in saturated porous media (equation 6.1.4.1) is solved numerically by a finite difference technique (DHI, 2005).

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-Q=S\frac{\partial h}{\partial t} \qquad (6.1.4.1)$$

Where:

$x, y,$ and z : axes of the model which are assumed to be parallel to the principle axes of the hydraulic conductivity tensor.

K_{xx}, K_{yy}, K_{zz} : hydraulic conductivity along the $x, y,$ and z : axes.

h : hydraulic head

Q : source/sink terms

S : storage coefficient. It switches between the specific yield and specific storage coefficient, for unconfined and confined conditions respectively.

Three types of boundary conditions can be specified (DHI, 2005):

- Prescribed hydraulic head on the boundary (Dirichlet conditions)
- Prescribed flux across the boundary (Neumann conditions)
- Prescribed head dependent flux on the boundary (Fourier conditions)

As explained in the previous chapter, the first two types of boundary conditions were used in this conceptual model.

The methodologies explained above are based on information provided by DHI (DHI, 2004a; 2004b; 2005; written communication, Douglas Graham (DHI), April 18, 2007; written communication, María Loinaz (DHI), April 12, 2007).

6.2 IMPLEMENTATION

The set up of the conceptual model in the numerical model (Mike She / Mike 11) included the input of all the spatial distributed data, initial values for the hydrologic parameters, and the specification of the initial and boundary conditions.

The main simulation specifications conditions used to perform preliminary runs of the model were:

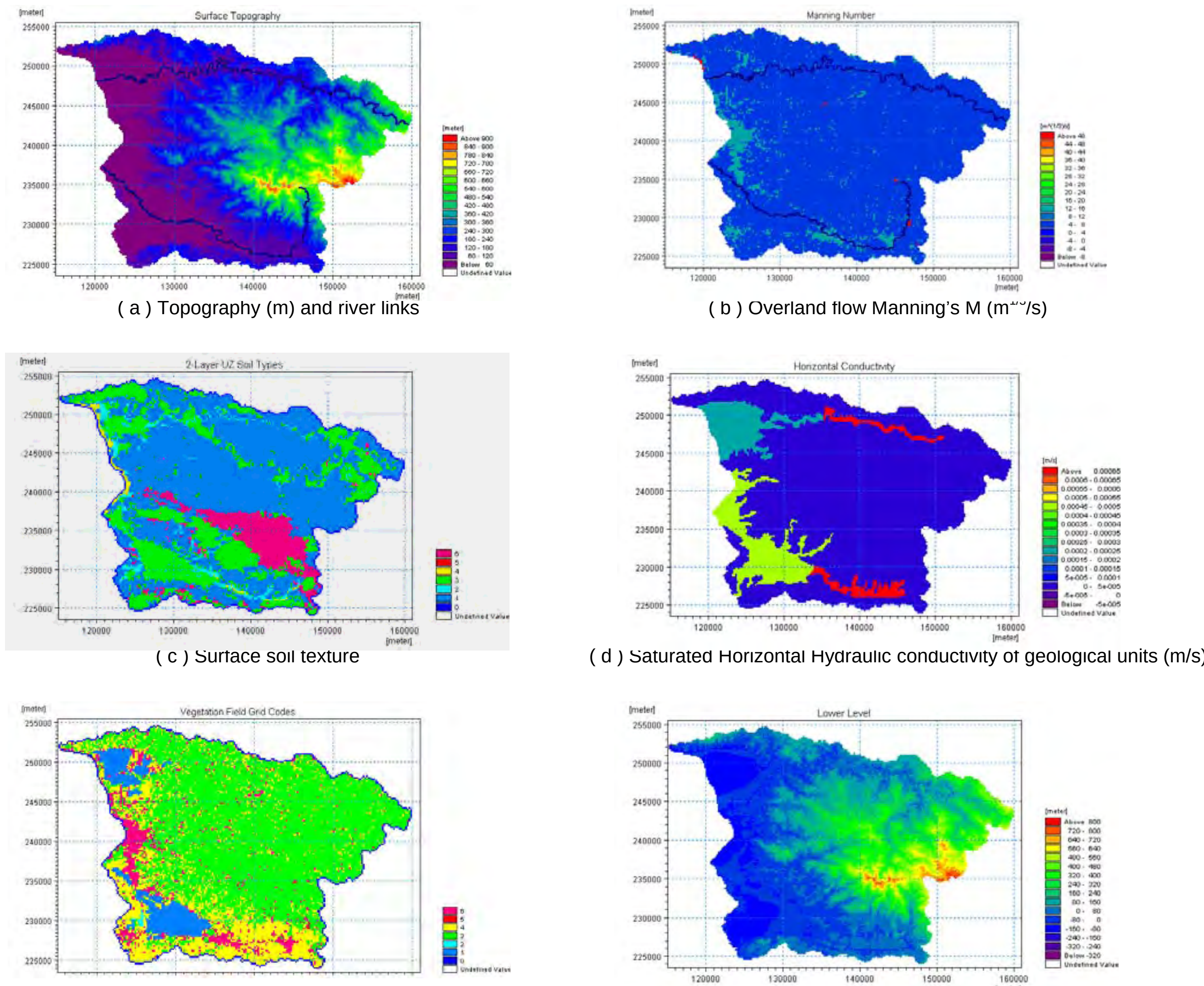
Model size:

- Overland and ground-water systems grid size (m): 200 X 200
- Number of computational points per layer: 21,172
- Maximum distance among computational points per river (m): 1,000
- Number of river flow grid points 304
- Number of river links: 720

Time step:

- Maximum allowed unsaturated zone and evapotranspiration: 2 hours
- Maximum allowed overland flow: 15 minutes
- Maximum allowed saturated zone: 6 hours
- River flow: 1 minute

Most of the spatially distributed data were input in the numerical model in ArcGis compatible formats (i.e. shape files), and then interpolated to the model grid. In Figure 6.2.1 some of the model preprocessed data is shown.



(a) Topography (m) and river links

(b) Overland flow Manning's M ($m^{1/3}/s$)

(c) Surface soil texture

(d) Saturated Horizontal Hydraulic conductivity of geological units (m/s)

(e) Land cover grid

(f) Aquifer bottom elevation (m)

Figure 6.2.1. Model preprocessed data samples for a preliminary run.

6.3 PRELIMINARY SIMULATIONS

Some preliminary runs of the integrated hydrologic model were performed to check the model response to variations in some parameter values in terms of the aggregated total annual discharge of the Añasco and Guanajibo rivers at the location of the flow gauging stations, and the ground-water heads at some locations within the study area. The aggregated total annual discharge is understood in this study as the sum of the total annual discharge of the two rivers. It is not the objective of these few preliminary runs to accomplish a model calibration which is beyond the scope of the present study.

The simulation period for the preliminary runs was the year 2004; therefore, the 2004 rainfall was used as model input. Stream flow results for these preliminary simulations were checked with 2004 reported data at the flow rate stations located at the Añasco and Guanajibo rivers.

Ground-water levels data for the study area is very temporal inconsistent. No ground-water level measurements for wells within the study area were available for the 2004 year; except for one well (USGS 180542067084000 PRASA 1 WELL, CABO ROJO, PR) whose measurements were being affected by pumping (personal communication, Sigfredo Torres (USGS), May 01, 2007). Therefore, data for other years were used in an attempt to compare the model results with approximate “realistic” values observed within the area. As was explained previously, the comparisons presented in this study are not intended to be a calibration of the model, but a way to check the model response to changes in the values of some parameters. Thus, simulated heads in the saturated zone were compared with measured data at four piezometers located in the lower valley of the Añasco river (Piezometer 17, Piezometer 3, Piezometer 28, and Piezometer 15); at four locations in the Central Guanajibo Valley, and at two wells located at the University of Puerto Rico at Mayagüez Campus (Figure 6.3.1).

Altitudes of the water table for the wells in the lower Añasco alluvial valley for September 3 (1981) and February 11 (1982) were reported by Díaz and Jordan (1987).

Rodríguez et al. (2004), in their investigation of the surface- and ground-water resources of the Mayagüez municipality from October 1, 1999, to September 30, 2002; reported that the ground-water levels in the south part of the lower Añasco valley had remained essentially the same since the 1987 study of Díaz and Jordan. However, for effects to this comparison, there is another possible limitation. It has to be mentioned that according to Díaz and Jordan (1987), these wells penetrated the surficial alluvial aquifer (zone II described in the section 4.4 of this study). Díaz and Jordan (1987) has reported that during the drilling of well 7 (Figure 4.4.2) the water table dropped approximately 5 m (16 ft) when the limestone was encountered, indicating that the alluvium and the limestone are hydraulically separated at that location; also they report that there is apparently poor connection between these materials in a well located in the Mayagüez airport. No information about the hydraulic connection at other locations of the lower Añasco Valley was found in the literature. This represents a limitation for the use of that data to make comparisons with the model results, given that the conceptualization of the geologic unit corresponding to the spatial location of those wells for this study (Añasco Alluvial-Lower valley aquifer, Figure 5.6.2) as a single layer aquifer, took into account not only the shallow permeable materials, but other deeper permeable materials, as described in section 5.6.

The reported altitudes of the water table at piezometers 17, 3, 28, and 15 (Diaz and Jordan, 1987) did not vary significantly between September 3 (1981) and February 11 (1982) (Table 6.3.1). Therefore, an average of the two measurements was obtained for comparison with the model preliminary runs results.

Along the water table contours presented originally by Colón-Dieppa and Quiñones-Márquez (1985) for the central Guanajibo valley (Figure 4.4.8), four locations were selected in which simulated ground-water heads results of preliminary simulations were compared with the reported elevation of water table.

The spatial locations of two wells located at the Civil Engineering department of the University of Puerto Rico at Mayagüez Campus (UPRM) correspond to the Volcaniclastic-, igneous-, and sedimentary-rock aquifer geologic unit conceptualized in this model. The measured data for October 02, 2005 were compared with preliminary runs results.

Table 6.3.1. Reported altitude of the water table at piezometers 17, 3, 28, and 15 in the Añasco Alluvial-Lower valley aquifer (Diaz and Jordan, 1987).

Piezometer	Altitude of water level (m). Datum is mean sea level			
	September 03 (1981)	February 11 (1982)	Difference between measurements (m)	Average (m)
17	0.47	0.52	-0.05	0.5
3	0.81	0.81	0.00	0.8
28	5.61	5.29	0.31	5.4
15	8.31	7.99	0.31	8.2

The first run was accomplished according with the initial parameter values, and boundary and initial conditions described in the previous chapter. Then few subsequent simulations were performed changing some parameter values (Table 6.3.2). During this process, when a simulation produces results closer to the streamflow observed values (the sum of the annual discharge at the two streamflow stations) that a previous one, usually it was used to initialize the next simulation. This procedure was done to improve the initial conditions for subsequent runs.

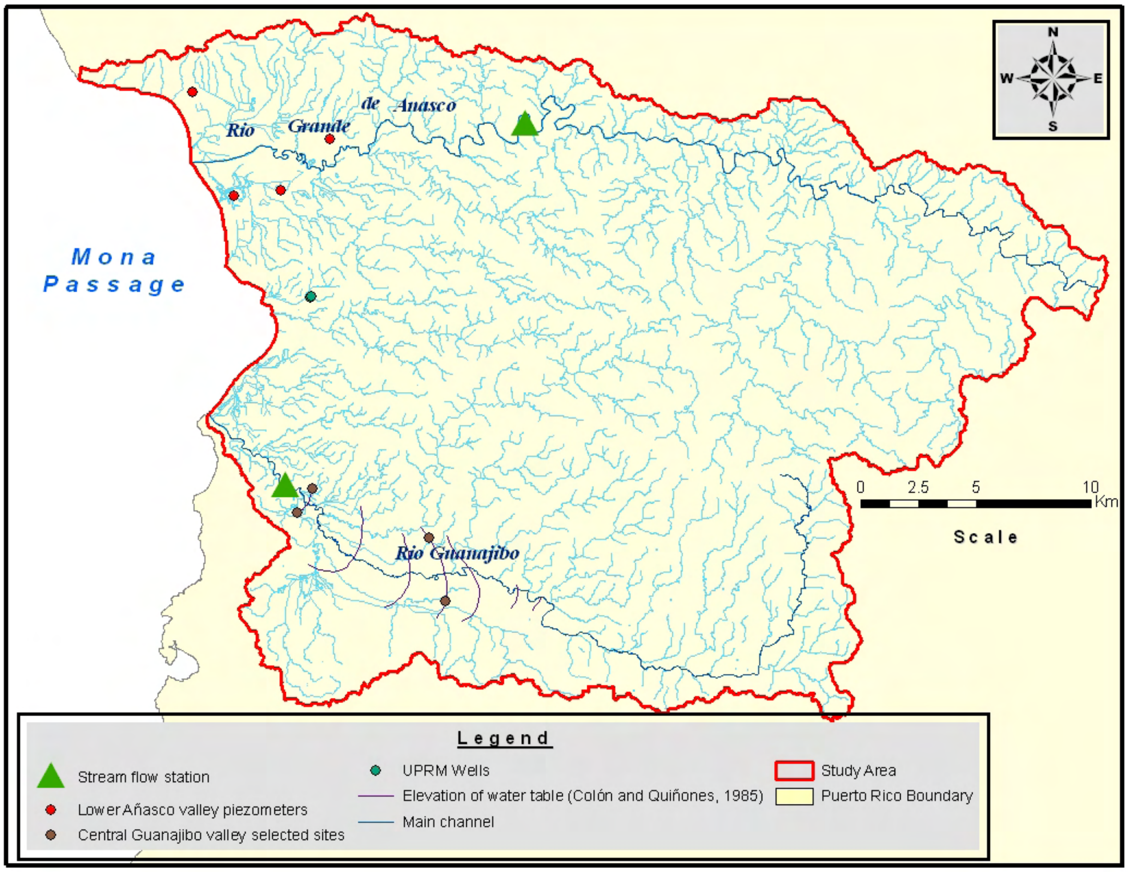


Figure 6.3.1. Location of stream flow stations, piezometers, wells and sites used to compare results of preliminary simulations.

Table 6.3.2. Parameter values changed for some preliminary simulations of the model.

Preliminary run	Parameter											
	ET	Groundwater				Surface water / Grounwater						
	Interception Coefficient (mm)	Horizontal Hydraulic Conductivity (m/s)				Overland-Groundwater Leakage Coefficient (1/s)						
		Volcaniclastic-, igneous-, and sedimentary-rock aquifer	Guanajibo Alluvial-Central and lower valley aquifer	Añasco Alluvial-Lower valley aquifer	Alluvial-Upper valley aquifer	Clay	Clay loam	Loam	Sandy	Gravel	Rock
PR_1	0.050	2.92E-07	4.75E-04	2.14E-04	6.84E-04	None	None	None	None	None	None
PR_2	0.005	2.92E-07	4.75E-04	2.14E-04	6.84E-04	None	None	None	None	None	None
PR_3	0.005	8.58E-05	4.75E-04	2.14E-04	6.84E-04	None	None	None	None	None	None
PR_4B	0.005	8.15E-07	4.75E-04	2.14E-04	6.84E-04	None	None	None	None	None	None
PR_5	0.005	8.15E-07	2.00E-03	5.00E-04	6.84E-04	None	None	None	None	None	None
PR_33	0.005	8.15E-07	4.75E-04	2.14E-04	6.84E-04	1.39E-06	2.22E-06	3.33E-06	1.39E-05	1.00E-02	2.66E-06

The aggregated value of total annual discharge for both stream flow stations is presented in Table 6.3.3, as long as the error relative to the measured value (e_r). The e_r was computed for the aggregated value of annual discharge for both stations. This statistic was computed using the following equation:

$$e_{r_{i,t}}(\%) = \left(\frac{Obs_{i,t} - Sim_{i,t}}{Obs_{i,t}}\right)*100 \tag{6.3.1}$$

Where:

$e_{r_{i,t}}(\%)$: error relative to the measured value at location i and time t

$Obs_{i,t}$: measured value at location i and time t

$Sim_{i,t}$: simulated value at location i and time t

Average reported altitude of the water table (Obs) for September 3 (1981) and February 11 (1982) at piezometers located in the Añasco Alluvial-Lower valley aquifer; and averaged simulated head elevations for September 3 and February 11 at the same locations are presented in Table 6.3.4, as well as the residual (E) between them. The residual was computed by:

$$E_{i,t} = Obs_{i,t} - Sim_{i,t} \tag{6.3.2}$$

Table 6.3.5 presents the generalized water-table elevation during June 1980 at four locations in the central Guanajibo valley, and the simulation average head elevation for June, as well as the residual (E) between these to values. The observed water level for October 2, 2005 at the two wells located in the UPRM, and the simulated heads in the saturated zone for those locations at the same date in 2004 is presented in the Table 6.3.6.

Table 6.3.3. Measured (Obs) and simulated (Sim) annual discharge at the Añasco and Guanajibo stream flow stations for some preliminary runs of the model.

Preliminary run	Stream flow at Añasco and Guanajibo rivers						
	Annual (Mm^3/year)						
	Añasco		Guanajibo		Total		
	Obs	Sim	Obs	Sim	Obs	Sim	e_r (%)
PR_1	409.51	54.58	217.40	54.37	626.90	108.96	82.62
PR_2	409.51	61.38	217.40	119.24	626.90	180.61	71.19
PR_3	409.51	1026.72	217.40	1094.14	626.90	2120.85	-238.31
PR_4B	409.51	199.89	217.40	221.91	626.90	421.80	32.72
PR_5	409.51	212.94	217.40	209.27	626.90	422.20	32.65
PR_33	409.51	330.75	217.40	321.91	626.90	652.65	-4.11

(Mm^3/year) = Millions of cubic meter per year

Table 6.3.4. Average reported altitude of water level (Obs) for September 3 (1981) and February 11 (1982) at piezometers located in the Añasco Alluvial-Lower valley aquifer, and averaged simulation head elevation for September 3 and February 11 (2004) (Sim).

Preliminary run	Groundwater wellls - Añasco lower valley											
	Piezometer 17			Piezometer 3			Piezometer 28			Piezometer 15		
	Obs*	Sim*	E** (m)	Obs	Sim	E (m)	Obs	Sim	E (m)	Obs	Sim	E (m)
PR_1	0.5	2.0	-1.5	0.8	2.6	-1.8	5.4	6.6	-1.1	8.2	11.1	-2.9
PR_2	0.5	2.4	-1.9	0.8	2.7	-1.9	5.4	6.5	-1.1	8.2	10.3	-2.1
PR_3	0.5	5.4	-4.9	0.8	25.1	-24.3	5.4	14.6	-9.2	8.2	28.0	-19.9
PR_4B	0.5	2.6	-2.1	0.8	3.2	-2.4	5.4	6.9	-1.5	8.2	11.4	-3.3
PR_5	0.5	2.9	-2.4	0.8	2.6	-1.8	5.4	7.6	-2.1	8.2	11.7	-3.5
PR_33	0.5	2.2	-1.7	0.8	1.9	-1.1	5.4	5.7	-0.3	8.2	8.2	-0.1

*Units are meters over mean sea level
**E: Residual

Table 6.3.5. Generalized water-table elevation during June 1980 (Obs) at four locations in the central Guanajibo valley, and simulation average head elevation for June (2004) (Sim).

Preliminary run	Central Guanajibo valley selected sites											
	Site 1			Site 2			Site 3			Site 4		
	Obs*	Sim*	E** (m)	Obs	Sim	E (m)	Obs	Sim	E (m)	Obs	Sim	E (m)
PR_1	5.0	10.9	-5.9	5.0	10.2	-5.2	20.0	22.6	-2.6	20.0	22.1	-2.1
PR_2	5.0	9.9	-4.9	5.0	9.3	-4.3	20.0	22.2	-2.2	20.0	21.7	-1.7
PR_3	5.0	24.3	-19.3	5.0	23.9	-18.9	20.0	38.9	-18.9	20.0	40.1	-20.1
PR_4B	5.0	12.1	-7.1	5.0	11.2	-6.2	20.0	25.9	-5.9	20.0	23.5	-3.5
PR_5	5.0	15.9	-10.9	5.0	15.1	-10.1	20.0	26.0	-6.0	20.0	24.7	-4.7
PR_33	5.0	11.1	-6.1	5.0	10.3	-5.3	20.0	23.5	-3.5	20.0	21.2	-1.2

*Units are meters over mean sea level
**E: Residual

Table 6.3.6. Measured altitude of water level (Obs) for October 2 of 2005 at wells located in the UPRM, and simulation head elevation for October 2 of 2004 (Sim) at those locations.

Preliminary run	Groundwater wellls - UPRM					
	Well CP			Well CO		
	Obs*	Sim*	E** (m)	Obs*	Sim*	E (m)
PR_1	13.3	20.0	-6.7	14.1	24.7	-10.7
PR_2	13.3	18.9	-5.6	14.1	24.7	-10.7
PR_3	13.3	25.3	-12.0	14.1	28.8	-14.7
PR_4B	13.3	18.5	-5.2	14.1	22.1	-8.1
PR_5	13.3	15.3	-2.0	14.1	18.8	-4.7
PR_33	13.3	11.3	1.9	14.1	15.4	-1.4

*Units are meters over mean sea level
**E: Residual

Observed and simulated monthly discharges at the stream flow stations at the Añasco and Guanajibo rivers are presented in Figures 6.3.2 and 6.3.3, respectively. The monthly discharges at both stations were very low compared with the measured values for the initial run (PR_1) during all months. To improve the results, for the next simulation (PR_2), the maximum interception storage capacity was reduced by modifying the value of the interception storage capacity parameter. The new value adopted (Table 6.3.2) has been used for other similar modeling efforts in Hawaii (Sahoo et al., 2006).

The reduction in the interception storage capacity value increased the flow in the rivers, as was expected, evidenced by the reduction in the error e_r (Table 6.3.3). However, the annual flow rate was too low compared with the measured value. An inspection of the measured and simulated mean daily flow rate hydrograph for both rivers showed that the base flow was too low for both cases during the year. Consequently, the value of the saturated horizontal hydraulic conductivity for the Volcaniclastic-, igneous-, and sedimentary-rock aquifer geologic unit (Figure 5.6.2) was increased for the PR_3 simulation (Table 6.3.2). Monthly discharge presented in Figures 6.3.2 and 6.3.3, and errors shown in Table 6.3.3 reflects that the change in the hydraulic parameters produced too much flow at the stream flow stations for this simulation (PR_3). An inspection of the measured and simulated mean daily flow rate hydrographs for both rivers showed that the base flow for the rivers increased for this simulation, as expected, but the volume was too great for this condition. Therefore, for subsequent simulations, the value for the saturated horizontal hydraulic conductivity for the Volcaniclastic-, igneous-, and sedimentary-rock aquifer geologic unit was progressively reduced up to a value specified in simulation PR_4B (Table 6.3.2), when the base flow seemed reasonable when comparing the measured and simulated mean daily flow rate hydrographs for both rivers. For simulation PR_5, values of saturated horizontal hydraulic conductivity at the Guanajibo Alluvial-Central and lower valley, and Añasco Alluvial-Lower valley aquifer geologic units were increased. This change reduced slightly the errors between measured and observed values of stream flow (Table 6.3.3), but increased the residual (E) presented in tables 6.3.4 and 6.3.5 in comparison with the previous simulation results (PR_4B), except for one piezometer.

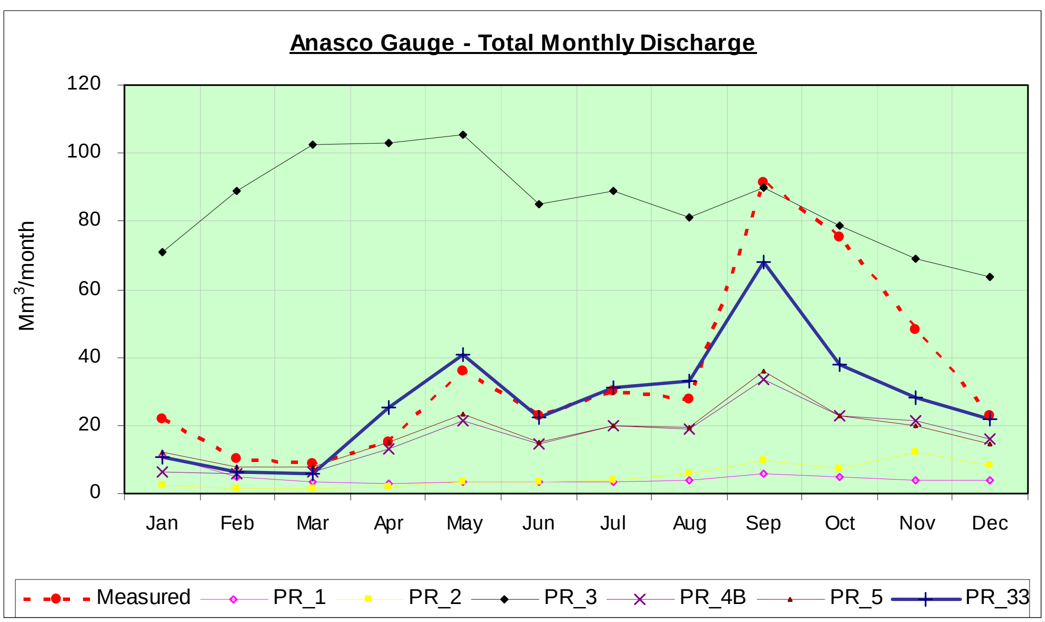


Figure 6.3.2. Total monthly discharge at the Añasco stream flow station.

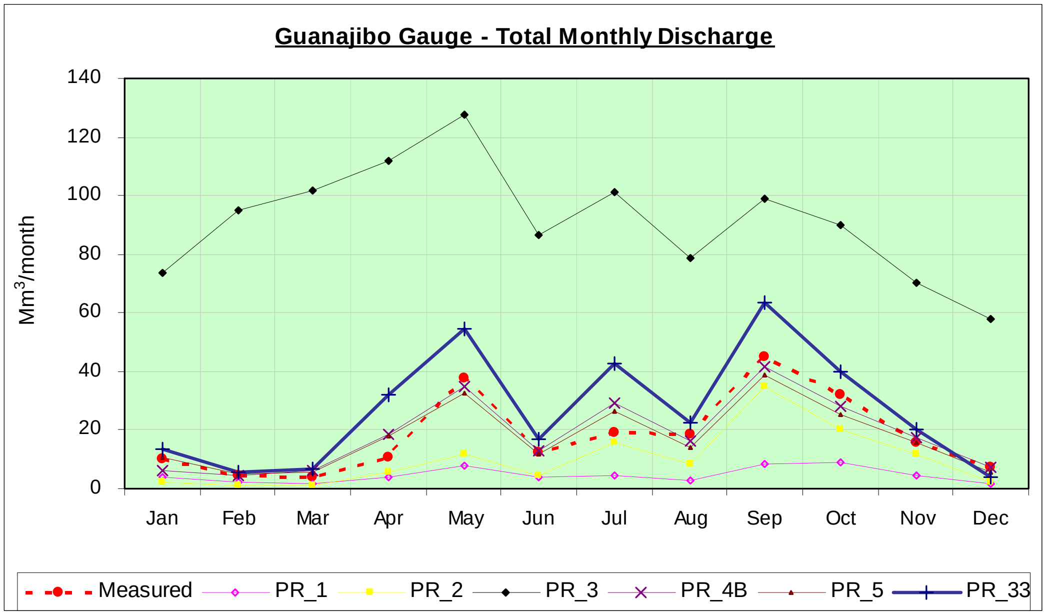


Figure 6.3.3. Total monthly discharge at the Guanajibo stream flow station.

Simulation run PR_33 was initialized from a previous simulation in which the ground-water heads in the lower Añasco and Central Guanajibo valleys were found to be closer to the reported altitude of water levels than in simulation PR_5. For simulation PR_33 a spatially distributed overland-ground-water leakage coefficient was included in the model. This coefficient is used in the computation of interchanged water between overland flow and the saturated zone when the vadose zone disappears, because the soil profile becomes saturated (DHI, 2005). When this coefficient is not included in the model, this exchange is calculated based on the vertical hydraulic conductivity of the upper layer in the saturated zone and the hydraulic gradient between the surface water level and the ground-water table (DHI, 2005). According with DHI (2005), based on the saturated hydraulic conductivities of the soils (DHI, 2005), a rough estimate of values for overland-ground-water leakage coefficient can be made. For simulation PR_33, the values of this coefficient were assumed to be spatially distributed according with the surface soil texture map shown in Figure 5.5.2. These values were assumed to be equal to the saturated hydraulic conductivities specified values for surface soils textures in the vadose zone of the model.

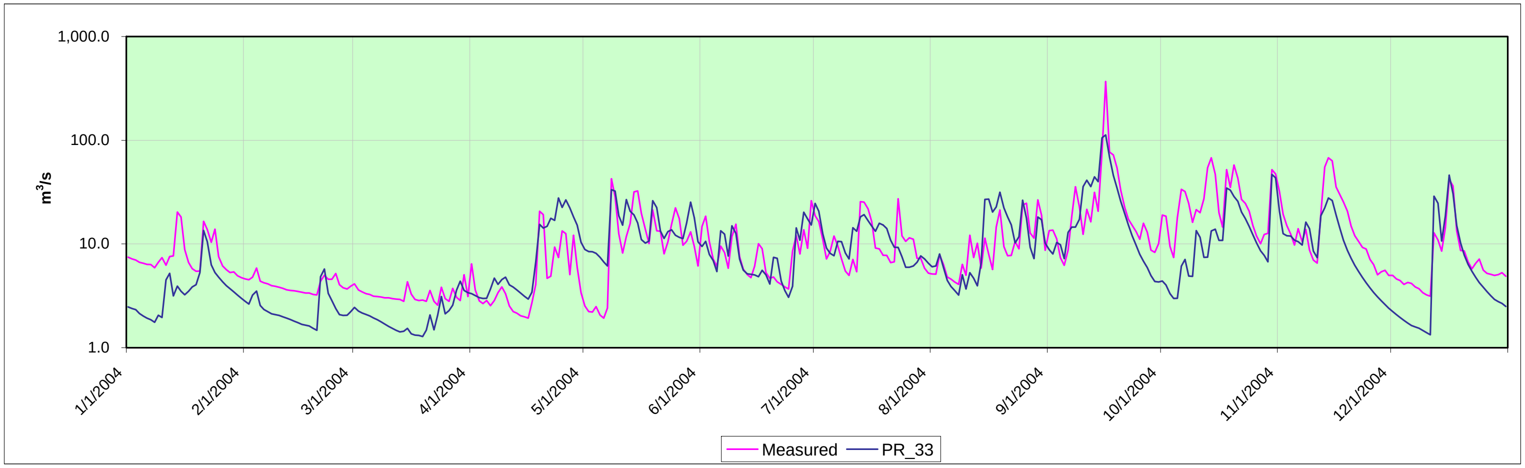
Residuals (E) presented in tables 6.3.4, 6.3.5 and 6.3.6 were reduced in PR_33 compared with PR_5. Results for simulation PR_33, also, indicated a closer agreement between the measured and observed aggregated (both rivers) value of annual flow discharge at stream flow stations than in previous runs presented in Table 6.3.3, evidenced by the reduction in e_r .

Figures 6.3.4 and 6.3.5 shows the daily mean discharge for observed and simulated values at the Añasco and Guanajibo stations respectively for preliminary simulation PR_33. Logarithmic scales are presented to facilitate visualization. The higher peak in the measured time series at the Añasco stream flow station is underestimated by the model (isolated point in the upper right part of Figure 6.3.4 (b)). Figure 6.3.5 (b) shows that most of the time during the year the mean daily flow rate at the Guanajibo station was overestimated by the model for preliminary run PR_33 (points above the line).

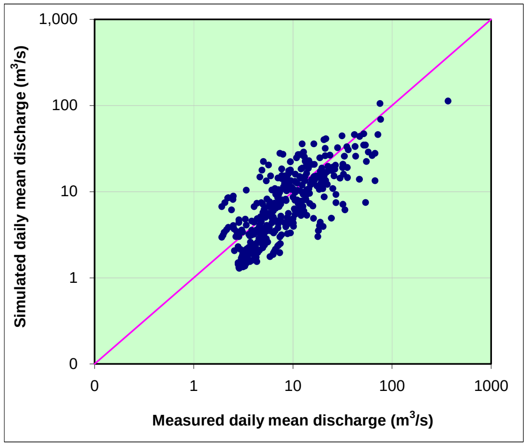
With the purpose of illustrating the capabilities of an integrated hydrologic model to produce a water budget, water balance results for preliminary run PR_33 are presented in Figure 6.3.6. Actual ET for preliminary run PR_33 was 1007 mm. The approximate average reference evaporation for the study area based on the data presented in Figure 4.2.5 is 1,760 mm/year. Therefore, an effective crop coefficient for this preliminary run would be (1007 mm / 1825 mm) = 0.57. This value is lower than the crop coefficients associated with the majority of land cover indicating that the potential evapotranspiration for the vegetation could not be satisfied for this preliminary run. River base flow was only 33 mm, which represents less than 2% of the total rainfall for the simulated year. On-hundred and seventy-three millimeters left the study area as overland flow across model boundaries for that preliminary run, probably mostly to the Mayagüez Bay, however some of this water may have moved across the other three boundaries. The relatively high value of overland flow across boundaries for that preliminary run is probably due, in part, to the fact that the Yagüez River was not simulated explicitly using Mike 11, rather stream flow in that watershed was simulated as overland flow. Sixty millimeters of ground-water flow entered the Mayagüez Bay directly via diffuse ground-water discharge for that preliminary run. Because no-flow boundaries were specified at the other three boundaries, all of the ground-water crossing model boundaries represents ground-water discharge to the bay.

During the simulated year, ground-water storage decreased significantly (261 mm). Normally the long term annual average change in aquifer storage is approximately zero (personal communication, Dr. Eric Harmsen (UPRM), April 24, 2007). This result indicates that for this preliminary run water was being released from storage as reflected by dropping ground-water levels at certain locations within the model area. One possible cause of the negative change in groundwater storage, for example, could be that aquifer recharge, (an internal boundary) was too low. An other possible cause could be, the fact that the initial condition for ground-water head data was assumed to be at the ground surface initially (for preliminary run PR_1), and a warming period was not performed before the preliminary runs. If the calibration of this model is attempted in future studies, a warming period of sufficient length needs to be performed to assure that the model is not readjusting itself throughout the simulation to non-realistic initial conditions. This should be done before sensitivity or calibration runs are made. Also, during future model calibration efforts, an attempt should be made to obtain an independent estimate of the annual change in groundwater storage and to bring the simulated results into close correspondence with this estimate.

Head elevations in the saturated zone for preliminary run PR_33 have been found to be several meters above the ground-surface within some valleys (e.g. 50 meters). These heads could likely become lower when the model is calibrated, because during the preliminary runs the ground-water levels in the mountainous areas (which can have a strong influence on the heads in the valleys) had not yet reached a pseudo-steady condition, which can be achieved by imposing a warm up period of sufficient length.

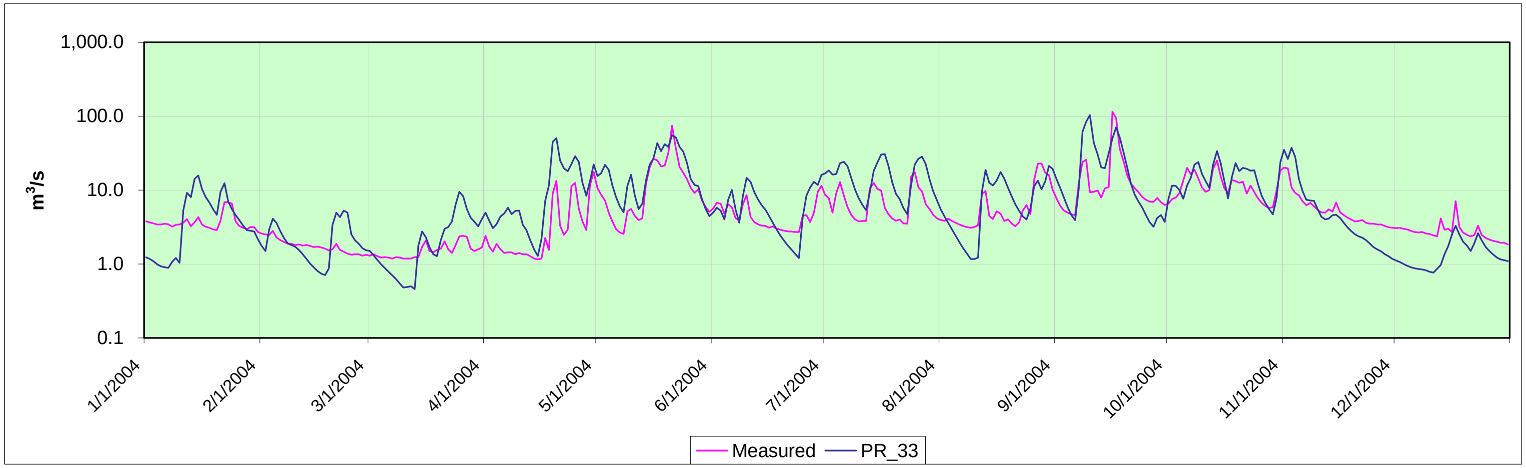


(a)

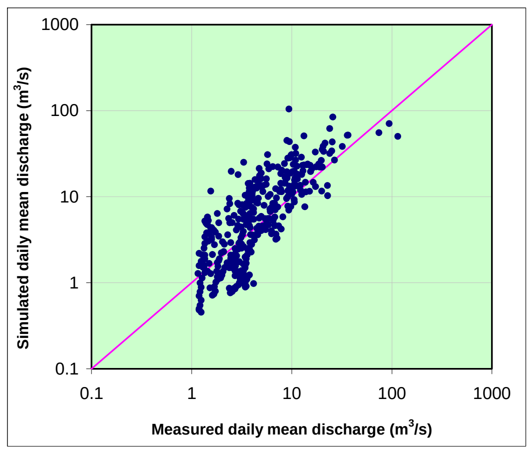


(b)

Figure 6.3.4. Daily mean discharge measured and simulated results from preliminary simulation PR_33 at Añasco River stream flow station: (a) date vs. stream flow, (b) measured vs. simulated stream flow.



(a)



(b)

Figure 6.3.5. Daily mean discharge measured and simulated results from preliminary simulation PR_33 at Guanajibo river stream flow station: (a) date vs. stream flow, (b) measured vs. simulated stream flow.

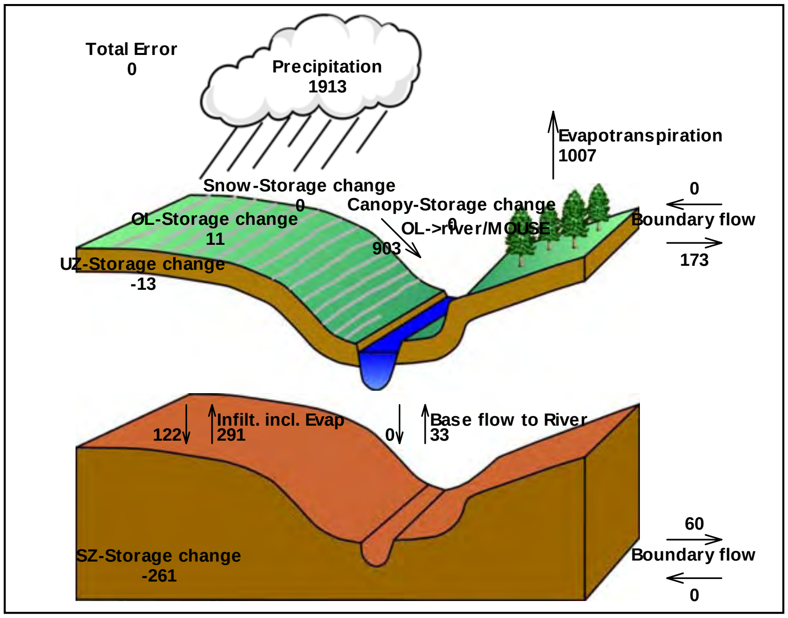


Figure 6.3.6. Annual entire basin water balance results for the preliminary run PR_33 (Output from Mike She) (These results are for illustrative purposes only. This is not a calibrated model. These results should not be used for water resources planning or other studies; see Chapters 6 and 7).

Figure 6.3.7 shows the altitude of water table contours reported by Díaz and Jordan (1987) for September 3, 1975, along with the interpolated average total head in the saturated zone in the alluvial valley for preliminary run PR_33. The contours of the altitude of the water table in the alluvial aquifer (zone II described in section 4.4) reported by Díaz and Jordan (1987), shows that ground-water patterns in this area are from the aquifer to the Río Añasco, Caño La Puente, and Caño Boquilla. The simulated contours for preliminary run 33 show a general pattern of ground-water flow towards the coast. The magnitude of the hydraulic gradients simulated by the model are consistent with the observed data.

Many causes could explain the differences in the shape of the head contours at this point of the model development. First, it has to be remembered that this is not a calibrated model. Also, more accurate topographic and bathymetric data would be needed, and a refinement in model grid cell size (with respect to those used for the preliminary runs) will likely be necessary to better reproduce the interactions between surface-water and ground-water. Other causes could be, for instance, the fact that the aquifer was conceptualized as one layer for this study, taking into account not only the shallower materials but other permeable materials (e.g. limestone), whereas the contours reported by Díaz and Jordan (1987) are for the shallow materials (zone II described in section 4.4). Another hypothesis for the difference in the shape in the head contours may be that the saltwater wedge at the coast is acting as a restriction for groundwater flow and effectively forcing water to the streams. Still another hypothesis is that the streambed conductances are higher than assumed in the model and consequently groundwater near the streams flow to the streams instead of toward the coast. An important use of the model could be generating hypotheses like those given above, which can later be investigated.

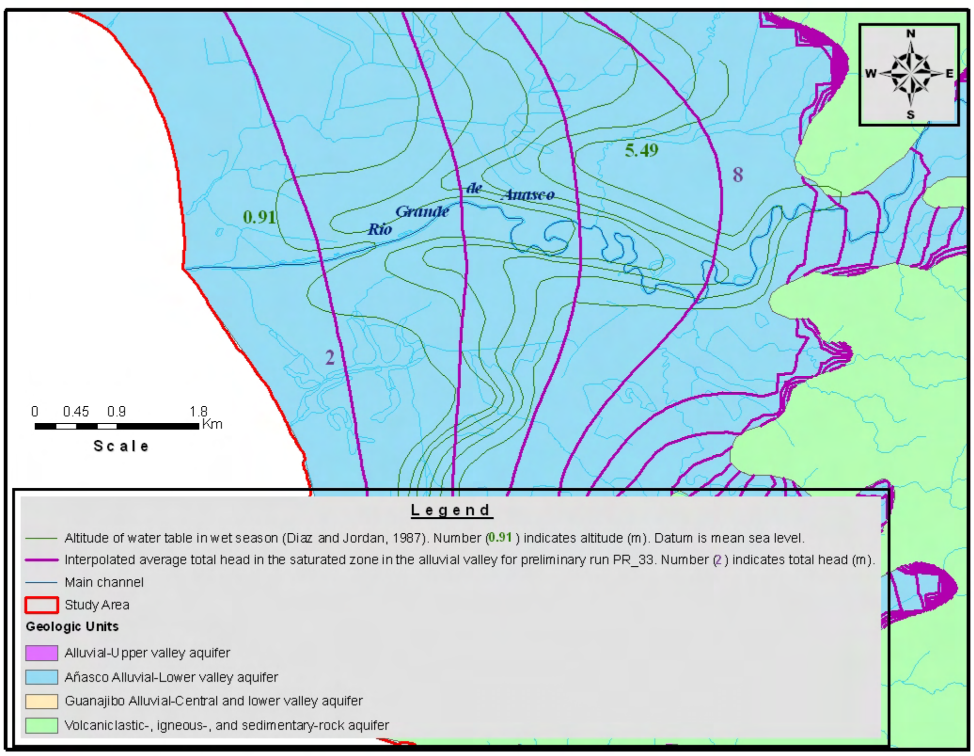


Figure 6.3.7. Altitude of water table in wet season, September 3, 1981, contours reported by Díaz and Jordan (1987) along with the interpolated average total head in the saturated zone in the alluvial valley for preliminary run PR_33.

Figure 6.3.8 shows the altitude of water table contours presented by (Veve and Taggart, 1996) and originally reported by Colón-Dieppa and Quiñones-Márquez (1985) for June 1980, along with the interpolated average total head in the saturated zone in the alluvial valley for preliminary run PR_33. It is observed that the general ground-water flow pattern in this area is towards the coast following the general topography. The magnitude of the hydraulic gradients simulated by the model is consistent with the observed data. However, it is recalled that the contours observed and simulated are not temporal consistent.

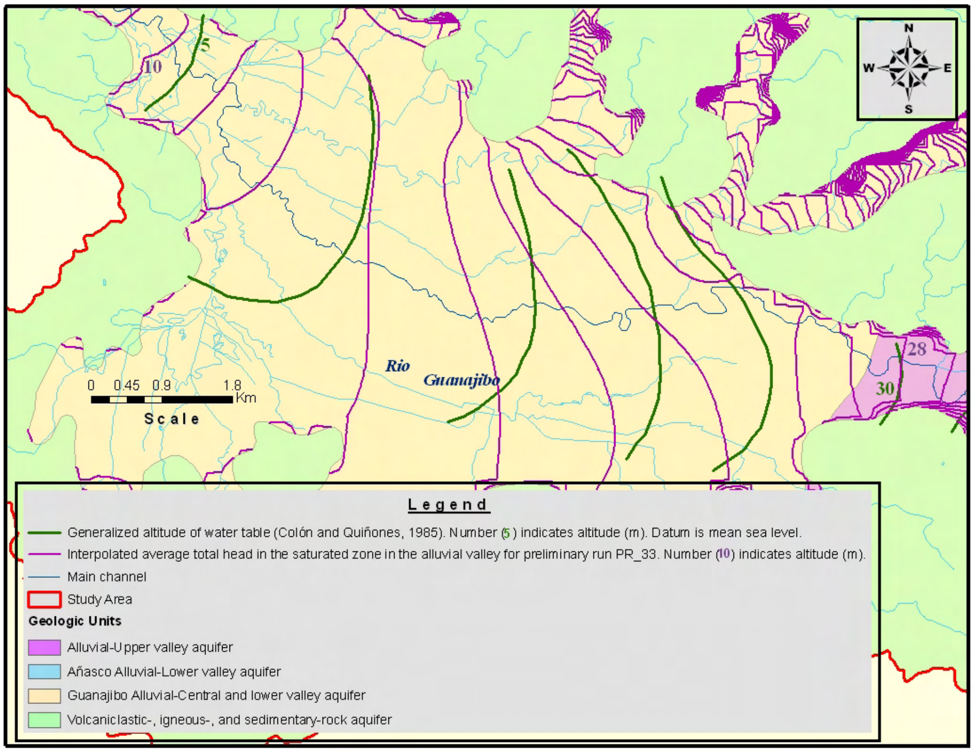


Figure 6.3.8. Generalized ground-water elevation contours originally reported by Colón-Dieppa and Quiñones-Márquez (1985) along with the interpolated average total head in the saturated zone in the alluvial valley for preliminary run PR_33.

Figure 6.3.9 shows the interpolated average total head in the saturated zone in the alluvial valley of Río Yagüez for preliminary run PR_33. It is observed that the general ground-water pattern in this area for preliminary run 33 is towards the coast following the general topography. According with Rodríguez et al. (2004), for this area, ground-water movement may has a predominant westward direction toward the coast with possible local flow components nearby river streams in the upper zone of the Mayagüez hydrogeologic terrain 1 (MayHT1, described in section 4.4); and a regional westward dominant movement in the lower zone.

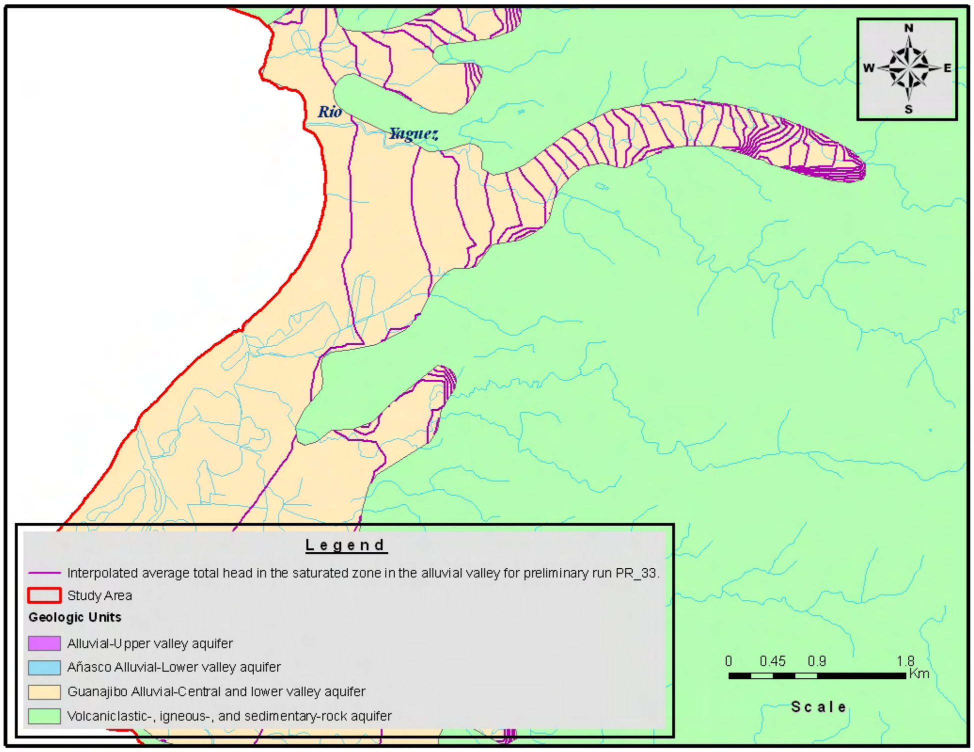


Figure 6.3.9. Interpolated average total head in the saturated zone in the alluvial valley of Río Yagüez for preliminary run PR_33.

It should empathized that the results of preliminary runs of the model here presented (e.g. Figures 6.3.6 to 6.3.9) are for illustrative purposes only and should not be used by other hydrologic evaluations or studies. These results are from few preliminary runs, the model is not calibrated, and the ground-water levels data used to compare is not temporal consistent. Recommendations for calibration of this model in future studies are presented in Chapters 7 and 8.

7 STUDY LIMITATIONS

The USGS 1:20,000-scale 7.5-minute topographic quadrangle maps which are entirely or partially included in the aerial extent of the study area and their publication date are: Bayaney (1982), Central_La_Plata (1964), Mayagüez (1964), Monte_Guilarte (1960), Maricao (1960), Puerto_Real (1966), Rincon (1966), Rosario (1964), Sábana_Grande (1966), San_Germán (1966), San_Sebastián (1958). The range of the publication dates is from 1960 to 1982, and most of them were published in the decade of the sixties. Any changes in land elevation from the date in which the topographic quadrangles were developed and the year used for calibration purposes in future studies would not be taken into account in the model, and therefore this would represent a potential source of error in the model. Also, the reader is warned that this model has the implicit limitation of the scale of the topographic quadrangles (1:20,000). In futures studies, if more temporarily consistent (regarding to the year of calibration); or more detailed elevation data are available, it should be used instead of the one used in this study.

Satellite imagery dated 1991-92 was used in the development of the digital map of the forest type and land cover (Helmer et al., 2002). The use of more updated land cover / use information for the study area in future studies could improve the results of this model. Also, the reader is cautioned that this conceptual model has the implicit limitations of the work done by Helmer et al. (2002) in the development of the digital map of the forest type and land cover. For more details, the reader is referred to Helmer et al. (2002).

The gap filling process for rainfall data was simplistic, assuming that precipitation data was similar in stations located within the study area. This, however, may not be true in a watershed with great diversity of features as the Mayagüez Bay drainage basin. In the future, as new analyses of rainfall data in the area are performed, the filling data process could be changed, and evaluations of the sensitivity of the spatial distribution of this variable in the model could be made. Also, the spatial distribution of rainfall was assumed based on a Thiessen polygon approach in this model, however, if future studies of this variable over the study area reflect a more accurate distribution, those changes have to be incorporated in this model given the influence that this condition could have on hydrologic modeling.

The sub watersheds of the lakes Guayo, Yahuecas, and Prieto were assumed not to be part of the Mayagüez drainage basin. However, given that those areas could potentially contribute with water to the Mayagüez bay drainage area during events in which the water level at the lakes is higher than the elevation of the spillway, this assumption constitutes one limitation of the model and a source of error. If future studies attempt to calibrate the model, this assumption has to be verified with water level data of the lakes for the specific period of calibration.

Numerous rivers, streams, and channels drain the study area. In this model most of them are conceptualized to be simulated as overland flow, and only the main two rivers were included to be simulated in the numerical model Mike 11. This constitutes one of the limitations of the model. This limitation is not expected to have large influence in the estimation of the annual water budget at a basin scale, however, this assumption has to be verified in future studies.

Non-availability of detailed cross section information of the rivers at some places during the development of this study was very evident. For this reason, several assumptions about the cross section shape and altitude were made in this model for some river reaches (as explained in section 5.3.3). The altitude of the cross sections for this model were made based on the elevation contours of the USGS topographic quadrangles for the study area which were published mainly in the decade of the 1960's, having a scale of 1:20,000. Also, the delineations of the main channel of the Añasco and Guanajibo rivers were made based on the USGS topographic quadrangles. If in future studies, more detailed topographic data become available for the rivers in the area, these data should be included in the model. It is not the objective of this model to produce a detailed hydraulic model for the Añasco and Guanajibo rivers, and it is not intended to be used in river / channel hydraulic modeling-specific studies.

This model does not take into account the diversion of waters from the Añasco and Guanajibo rivers (e.g. by public supply or self supply industrial, commercial, agricultural or domestic facilities) which are subsequently returned to the river, or are discharged out of the basin (e.g. by ocean outfalls). The redistribution of water within the watershed and any discharge to ocean outfalls has been assumed not to have a large influence on the annual water budget estimation for the entire basin. This assumption should be verified in future studies with reliable information about the volumes of water diverted from the river network, and discharged to the river network, or out of the basin.

Daily reference evapotranspiration estimates (Harmsen, 2006; unpublished data) used in this study have the implicit limitations and assumptions of the previous studies and methods used. For details about the limitations of previous studies, the reader is referred to the references: Hargreaves and Samani (1985), Harmsen et al. (2002), Harmsen and Gonzalez (2005), and Goyal et al. (1988).

After the development of the model, more accurate coordinates of the Maricao Forest station were obtained from Lugo (2005). The more accurate location of this station would change the Thiessen polygon vertices location used for rainfall and evapotranspiration distribution in the model. Also the more accurate elevation of that station would change the estimates of reference evapotranspiration for that polygon (Harmsen, 2006; unpublished data). The correction of the distribution of rainfall and ET, as well as, a new estimate of the reference ET for that polygon have to be corrected in future improvements of this model and for calibration purposes. According with Lugo (2005) the coordinates and altitude of the Maricao Forest station are: 18º09’26” N; 67º00’14” W; and the altitude is 746 m.

The surface soil texture reclassification performed in this study did not taken into account the impermeable zones in urban areas. For future improvements of this model and calibration purposes, the urban areas should be delimited, and appropriate values of infiltration rate assigned.

Most of the literature reported values reviewed and taken into account for assigning parameter initial proposed values were not necessarily for the specific conditions of the study area (e.g., detention storage values reviewed were not necessary for tropical conditions) or did not correspond exactly with the categories (soil and land cover) conceptualized in this study. Therefore, the proposed initial parameter values presented in this study have to be considered simply as starting points and subject to adjustments during calibration efforts in future studies.

The assumption of no flow ground-water boundary condition along the surface water divide (except for the boundary at the bay) has to be studied and verified in future studies, given that no data were available during this study to support it. This assumption may not be appropriate at the location of the dams of the lakes Guayo, Yahuecas, and Prieto.

Lack of information related with the spatial distribution, extend, and thickness of the different layers and lenses of permeable materials for many zones within the study area is evident. Therefore, the ground-water conceptual model presented in this study is the result of a process in which educated assumptions had to be made; and responded to the necessity to perform a first preliminary attempt to develop an aquifer system conceptualization for a regional scale integrated hydrologic model. Therefore the model is not intended to be used in site specific, detailed, and /or local scale studies. It is the aim that this conceptual model be improved in future studies as more data is available or a better understanding of the aquifer system evolves.

The assumption that the ground-water withdrawals are not significant enough to be considered for the regional water balance estimation is a limitation of the model. If future studies attempt to calibrate the model, this assumption has to be verified with groundwater withdrawals data for the specific period of calibration.

Ground-water levels data for the study area is very temporal inconsistent. No ground-water level measurements were found for the 2004 year; except for one well whose measurements were being affected by pumping (personal communication, Sigfredo Torres (USGS), May 01, 2007). Also, ground-water level data presented by Diaz and Jordan (1987) for the lower Añasco alluvial valley corresponds to the alluvial material (zone II, zone II described in section 4.4), and may not be representative of the heads for the different permeable materials present in that area. The hydraulic connection among the different permeable materials can vary spatially within the alluvial geologic units defined in this study. Given that the saturated zone was conceptualized in this model as one-layer aquifer, the observed ground-water levels of only one of the permeable materials may not be representative of the heads simulated by the model. As a result, it is concluded that at the present time there is not sufficient data to calibrate the saturated zone of the model. Future efforts of collecting temporal consistent and spatially distributed ground-water data have to be made if a model calibration is attempted in the future.

According with the coupling between Mike She and Mike 11 (see section 6.1.2), the river-aquifer exchange depends partially on how accurately the river network can be represented in Mike She. The more refined the Mike She grid and the more detailed the topographic and bathymetric input data, the more accurately the river network, the land elevations, and the river-aquifer and overland-river exchange can be reproduced by the model. For preliminary runs presented in this study, a Mike She grid cell size of 200 m X 200 m was used as a first preliminary attempt to run the model avoiding long computational times. However, this grid cell size could be too coarse to well represent the river-aquifer and overland-river exchanges, especially in the mountainous areas where differences in elevation between adjacent cells have been observed to be large at some locations in the model. Therefore, future studies have to evaluate the applicability of this grid cell size (200 m X 200 m) for the specific topographic conditions of the study area. It is strongly recommended that the sensitivity of the results to reduction of the grid cell size be evaluated. If future studies attempt to study relations between ground-water and surface water, a refinement in the grid cell size will be necessary, as well as the input of more accurate / detailed topographic and bathymetric data in the model.

The river flow in this model was implemented in Mike 11 using the no flooding option (see section 6.1.2). Future studies should evaluate using the manual flood area option to assess if this improves the results of the annual water balance. In that option potentially flooded areas can be delineated by the user (DHI, 2005).

An inspection of the heads in the saturated zone for some cells at the eastern part of the model revealed drops of several meters between the first and the end day of the simulation for preliminary run PR_33. One reason for those changes could be that the initial condition for ground-water head data was assumed to be at the ground surface initially (for the first preliminary run), and a warming period was not performed before the preliminary runs. If future studies attempt to calibrate the model, a warming period of sufficient length has to be performed.

The flow rate results of preliminary runs at a temporal scale of two hours reflects numerical instabilities at the Guanajibo River at the computational point corresponding with the location of the streamflow station. These numerical instabilities should be addressed in future studies. Water levels in the location of the flow rate station at this river increased several meters above the bank elevation for some time steps, which could be due to these instabilities and / or the use of the no flooding option in this study.

The model presented in this thesis has to be understood as a preliminary first attempt to accomplish a regional scale conceptual model for an integrated hydrologic modeling. It is intended to be improved in future studies as more data becomes available and / or others have a better understanding of the hydrology in the area. Many assumptions were made in the development of the model given the limited data available and the complexity of the physical system. Those assumptions have to be verified by future studies to improve the present model. Before the model is used for simulation purposes, it has to first undergo a thorough calibration and validation.

8 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A preliminary integrated hydrologic regional conceptual model was developed for a coastal tropical watershed and implemented in an integrated, fully distributed, physically based, numerical model. Preliminary simulations of the model were performed to check the model response to the variation in some parameter values. Limitations and assumptions of the conceptual model were stated; and recommendations for its future improvement and calibration are presented at the end of this section and in the previous chapter.

The development of a tropical basin, regional scale, integrated hydrologic conceptual model to be implemented in a fully distributed, physically based, numerical model is a challenging task, which requires diverse information about the physical features of the system and measured data of the hydrologic variables. The Mayagüez drainage basin constitutes a system with a wide diversity of physical and hydrological features (e.g., geology, topography, climate, and land use), and in which the lack of available, temporally consistent, and spatially distributed information is frequently the case for many areas. Therefore, the model developed in this research has to be understood as a first preliminary attempt to perform a regional integrated hydrologic conceptual model of a complex system in which numerous assumptions had to be made. This study constitutes a starting point in the development of a model intended to be constantly improved in future years as more information becomes available or a better understanding of the system is gained.

In that sense, as this model can be refined, and undergo thorough calibration and validation procedures in future efforts, it could be useful in the study of the regional scale annual water balance, and of the relations between surface water and ground-water. Also, this model could be useful as a continuous database of the hydrological properties and data of the study area. As more data becomes available, this model can be updated, and in that way, improved throughout years.

The calibration of this model requires additional data than available at the present time. The published information available in the literature for the study area at the present time reveals a great lack of distributed and temporarily consistent data, which is necessary to calibrate and validate the model. Some of the complementary efforts that could serve to improve or calibrate the integrated hydrologic model are presented below:

- The collection of ground-water level data spatially distributed over the study area. Data of wells with fully penetrated screens, which averages ground-water levels among different hydrogeologic units would be useful for calibration. If that data is not available, data from wells with screens at different depths could be useful to study the hydraulic connection between permeable materials.
- The collection of well log information of wells drilled to the depth of the relatively impermeable bedrock would permit to check and improve the estimation of the thickness of the aquifer.
- The collection of data from rainfall stations distributed at different elevations and areas of the basin would compliment the USGS rainfall network over the study area; and allow for a more accurate analysis of the rainfall distribution within the basin.
- The use of temporally consistent information of rainfall, ground-water heads, and stream flow rate data is necessary for calibration purposes.
- If flow rate stations at the mouths of the Añasco, Guanajibo and Yagüez rivers are installed in the future, the collection of that information would be useful for calibration purposes of the model.
- Collection of directly measured actual evapotranspiration at different elevations (e.g. mountains and lower valleys) and at different land cover categories (e.g. forest, pasture, agriculture) over the study area would allow the use of this data to assist in the calibration (i.e. as an additional calibration target).

Additional recommendations were presented in the Study Limitation chapter (Chapter 7) of this thesis.

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