Estimation of Water Balance and Groundwater Processes of the Salinas to Patillas Area in Southeastern Puerto Rico for 1980 - 2010

By

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Abstract

This study describes the groundwater recharge and pumpage, and surface water distribution through a water balance model for the Salinas to Patillas agricultural area located over the alluvium of the eastern part of the Puerto Rico South Coast Aquifer. This area is influenced by the Patillas-Guamaní irrigation canals of the Guayama Irrigation District which is a subdivision of the Puerto Rico Electric and Power Authority (PREPA). The combined soil water and groundwater budgets are based on data collected during the last 31 years, from 1980 to 2010.

It is believed that recharge is as dependant on annual precipitation distribution as it is to annual total precipitation. It was estimated that the average annual percolation from precipitation from 1980 through 1993 was 15 percent of the total rainfall while 1994 through 2010 was 11 percent. Percolation from irrigation gradually decreased from the early 1980s to the mid 2000s as irrigation efficiency gradually increased during this period and irrigated area decreased. Based on water deliveries data by PREPA and irrigation efficiency estimates, it is theorized that in furrow irrigation fields about 20 percent of the irrigation water applied actually recharge the aquifer, where other 10 to 40 percent of the water that may recharge the aquifer in irrigated fields is the direct result of the interaction between precipitation and irrigation. In the same way, it is theorized that none of the water imported for drip irrigation percolates and that in sprinkler irrigated fields only about 5% of the imported water percolates, where all other percolation come from the interaction with precipitation.

For Guayama, Arroyo and Patillas, the general order of importance for groundwater recharge inputs was estimated as precipitation, streams, canals, irrigation and dams. In the Salinas area was the stream percolation the most important input, followed by precipitation, canals and irrigation. Irrigation canals are a very important source of groundwater recharge because of its continuous and safe input to groundwater. Estimated groundwater recharge from the two reservoirs within the study area was determined as negligible.

The Salinas to Patillas area experienced a reduction in groundwater pumpage after the sugarcane production stopped in the area due to the reduction in irrigation water requirement and in irrigated area. The greatest reduction in groundwater pumpage prior and after the end of sugarcane production was experienced by Arroyo (49 %) while Guayama experienced the least changes (11 %). Reduction in groundwater pumpage in Patillas and Salinas was estimated to be 27 and 14 percent, respectively.

In general, results from the model show a healthy aquifer in the Arroyo, Patillas and Guayama area in terms that net groundwater recharge where the vast majority of the years counted with average net recharge rates greater than 180 mm/yr. Results indicates that in the Salinas area the average net groundwater recharge was around 64 mm/yr and groundwater depletion to the point of possible saltwater intrusion occurred during the years 1980, 1983, 1991, 1993, 1994, 1995, 1997, 2000, 2001, 2002, and 2009 due to the high water extractions for public supply and for irrigation practices.

Two scenarios were studied as possible strategies for groundwater management in the Salinas area involving the irrigation canals and assuming that its development is feasible: 1) increase surface water imports from the canals to farms and decrease or eliminate groundwater extractions for irrigation practices, 2) create infiltration ponds that use collected runoff, treated wastewater and exceeding water from irrigation canal as source of artificial aquifer recharge in strategic areas. Mitigation on groundwater depletion in Salinas could be planned in such a way in which 75 percent of the irrigation water requirement is provided by the irrigation canals and 25 percent by pumpage. On the other hand, it was found that the use of 2 shallow infiltration ponds of a total volume of 12,335 m^3 that are constantly feeding the aquifer with percolated water produce positive net groundwater recharge even in the worst case scenarios and could increase the average net recharge from 64 to 236 mm/year.

Resumen

Este estudio describe el bombeo, la recarga de agua subterránea, y distribución de agua superficial a través de un modelo de balance hídrico para el área agrícola entre Salina y Patillas localizada sobre el aluvión al este del Acuífero Sur de Puerto Rico. Esta área está influenciada por los canales de riego Patillas-Guamaní del Distrito de Riego de Guayama que es una subdivisión de la Autoridad de Energía Eléctrica de Puerto Rico (PREPA por sus siglas en inglés).

Se cree que la recarga por precipitación es tan dependiente a su distribución anual como lo es al total de precipitación anual. Se estimó que la percolación promedio de parte de la precipitación para los años 1980 al 1993 fue el 15 por ciento de la lluvia registrada mientras que del 1993 al 2010 fue el 11 por ciento. La precolación por riego disminuyó gradualmente desde principios de los 80s hasta mediados de los 2000s a medida que la eficiencia de riego iba aumentando gradualmente durante este periodo y el área regada disminuía. Basado en data de entrega de agua por PREPA y estimados de eficiencia de riego, se teoriza que en campos regados por inundación de surcos la recarga del acuífero proveniente de riego fué alrededor del 20 por ciento, donde otro 10 a 40 por ciento del agua que podría recargar el acuífero en campos regados es el resultado directo de la interacción entre la precipitación y el riego. De la misma forma, se teoriza que nada del agua importada para riego por goteo percola y que en campos regados por aspersión solo percola el 5% del agua importada, donde el resto de la percolación viene de la interacción con la precipitación.

Para Guayama, Arroyo y Patillas, el orden general estimado en cuanto a la importancia de los insumos en la recarga del acuífero es la precipitación, los ríos y quebradas, canales, riego y reservas. En el área de Salinas fué la percolación de ríos y quebradas el insumo más importante, seguido por la precipitación, canales y riego. Los canales de riego son una fuente importante para la recarga del acuífero por su aportación continua y segura al agua subterránea. La recarga estimada proveniente de las dos reservas dentro del área de estudio es insignificante y se puede ignorar.

El área de Salinas a Patillas experimentó una reducción en el bombeo de agua subterránea luego que la producción de caña de azúcar se detuviera, esto debido a la reducción en el requerimiento de agua para riego y en el área regada. La mayor reducción en bombeo de agua subterránea entre antes y después de finalizada la producción de caña de azúcar ocurrió en el área de Arroyo (49%) mientras que en Guayama ocurrió el menor cambio (11%). La reducción en bombeo de agua subterránea en Patillas y Guayama se estimó en 27 y 14 por ciento, respectivamente.

En general, resultados del modelo muestran un acuífero saludable en el área de Arroyo, Patillas y Guayama en términos de recarga neta, donde la inmensa mayoría de los años contaron con recarga neta promedio mayores a los 180 mm/año. Resultados indican que en el área de Salinas la recarga neta del agua subterránea fue alrededor de 64 mm/año y que disminución en el agua subterránea al punto de posible intrusión salina ocurrió durante los años 1980, 1983, 1991, 1993, 1994, 1995, 1997, 2000, 2001, 2002, y 2009 debido al alto bombeo para uso publico y para practicas de riego.

Dos escenarios fueron estudiados como posibles estrategias para el manejo del agua subterránea en el área de Salinas, esto envolviendo los canales de riego y asumiendo que su desarrollo es factible: 1) incrementar los importes de agua para riego por parte de los canales de riego y disminuir o eliminar las extracciones de agua subterránea para practicas de riego, 2) crear charcas de infiltración localizadas en lugares estratégicos que usen agua colectada de escorrentía, agua tratada y el excedente de agua de los canales de riego como fuente de recarga artificial al acuífero.

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1. Introduction

1.1 Scope of the Study

This study describes the groundwater recharge and pumpage, and surface water distribution through a water balance model for the Salinas to Patillas agricultural area located over the eastern part of the Puerto Rico South Coast Aquifer which is influenced by the Patillas-Guamaní irrigation canals of the Guayama Irrigation District. The water balance model created for this purpose is based on estimates of daily soil moisture changes where the water outputs of the soil profile are seepage and evapotranspiration based on the inputs of infiltration from precipitation, applied irrigation, stream beds, irrigation canals and dams. Special emphasis is given to the alluvial valleys where most agriculture is located, receive most of agricultural water delivered by the irrigation canals, groundwater pumpage occur and where most infiltration for aquifer recharge has been reported to happen. This groundwater budget is based on data collected during the last 31 years, from 1980 to 2010 to account for the most recent changes in irrigated agriculture and land development of that region of Puerto Rico.

During the past hundred years, hydrologic conditions and aquifer recharge and development in Southeastern Puerto Rico have been highly dependant on irrigation water conveyance and application. This phenomenon has been studied at different scales and with different objectives by Capiel and Calvesbert (1976), Gómez-Gómez (1991), Ramos-Ginés (1994c) Quiñones-Aponte *et al.* (1997), Kuniansky *et al.* (2004), and Kuniansky and Rodríguez (2010), among others. According to modeling results published by Kuniansky and Rodríguez (2010), from the early 1900s through the early 1990s in the Salinas area the water imported to agricultural land for surface irrigation of sugarcane fields maintained a period of abundance in surface and subsurface water that was inexistent prior to this period and that considerably depleted past that period. It is believed that this pattern also occurred in the vicinity of Guayama, Arroyo and Patillas that, along with Salinas, constitute the Salinas to Patillas study area.

Abundance in surface and subsurface water due to fluxes induced by surface irrigation of sugarcane fields caused several modifications to the local hydrologic cycle, and to the local ecology and landscape. These modifications are highlighted by the landscape changes where irrigation return water caused a unique marine ecological development along the coastal line that can be better appreciated in the Jobos area of Salinas. Another factor is the economical impact that caused a vast development of the aquifer where large amount of groundwater was pumped for agricultural, thermoelectric, public and industrial purposes.

In 1993 the sugarcane production was discontinued in the Salinas to Patillas area and horticultural products took over as the main agricultural business. More importantly, the disappearing of the sugarcane caused a considerable reduction in surface water irrigation and irrigation water deliveries which subsequently caused a modification on the rate of aquifer recharge and groundwater extractions (Quiñones-Aponte *et al.*, 1997 and Kuniansky and Rodríguez, 2010). These new surface/subsurface aquifer interactions called for new planning of the use and distribution of water resources of the area causing a re-modification the local hydrologic cycle as well as to the local ecology and landscape.

Equitable implementation of new planning practices in the Salinas to Patillas area requires a better understanding of the factors that affect the sources and quantity of agricultural seepage flow during the transition period between sugarcane and horticultural production. Through a water balance approach, this report describes the sources, quantity and interactions of the elements of the hydrologic cycle in the Salinas to Patillas area which can be useful for planning purposes.

This report intends to be complementary to previous studies done by Quiñones-Aponte *et al.*, (1997) and Kuniansky and Rodríguez (2010) by providing a different approach on the estimation of aquifer recharge from irrigation water, irrigation canals and other agricultural water interactions with the aquifer. This is done by developing a numerical model of the surface/groundwater flow system that can be used to help evaluate the sources and quantity of agricultural seepage and net aquifer recharge. This report presents the methods used to estimate annual recharge to the groundwater flow system and annual groundwater pumpage from the system for the calendar years 1980 through 2010. It also presents some possible recharge sources not considered in previous studies along with different approaches on the estimation of net recharge from agricultural areas.

Although it is believed that the results presented here closely follow the actual surface/groundwater interactions between 1980 and 2010 in the Salinas to Patillas area, this is not necessarily what exactly happened in the study area during the study period, but what can be estimated using the created model. On the other hand, aquifer recharge from agricultural land may also be affected by groundwater levels and by aquifer characteristics not accounted by the model. Environmental factors not considered that may affect recharge include rate and duration of precipitation and localized flooding owing to discharges from mountain-front streams. Management factors that may affect recharge not considered include: a) irrigation application time, b) recycling and reuse of irrigation water c) specific cropping patterns d) independent crop water use, and e) farm based rates and depths of groundwater pumping. Nonetheless, modeling was performed with all the physical data available using mathematical models that most closely represent the actual conditions and practices in the study area.

1.2 General Setting

The Puerto Rican north counts with abundant precipitation and water resources as stated by Capiel and Calvesbert (1976). The south coast is dry offering the most critical conditions for agriculture development because of precipitation deficit (Capiel and Calvesbert, 1976). The south relies on infrastructure, irrigation districts and water transfer from the north (Ortiz-Zayas *et al*., 2004) to support the water demand from agriculture and other sectors.

Puerto Rico has four irrigation districts, all operated by the Puerto Rico Electric Power Authority (PREPA). These districts are:

- the Guajataca District, supplied by the Guajataca Reservoir which covers the municipalities of Isabela, Moca, Aguadilla and Aguada,
- the South-west system, supplied by systems of underground tunnels and surface canals between the Yauecas, Guayo, Prieto, Luchetti and Loco Reservoirs, covers the Lajas Valley and its neighboring areas including the municipalities of Yauco, Sabana Grande, Guánica, Lajas and Cabo Rojo,
- the South Coast District in Juana Díaz, supplied by the Matrullas, Guineo and Guayabal Reservoirs, covers the agricultural area in the south coastal plain from eastern Ponce to western Salinas,
- and, finally, the South Coast District in Guayama which supplied by the Patillas, Melanía and Carite Reservoirs covers the agricultural area in the southeastern coastal plain of the municipalities of Salinas, Guayama, Arroyo and Patillas. The Guayama irrigation district regulates the Patillas-Guamaní canals located within the study area, or the area subjected to the water balance estimation that produced the current report.

The irrigation canals were built in the first part of the 20th century after the Public Irrigation Systems Law of Puerto Rico passed in 1907 (Fas Alzamora, 2009), to supply water to the then growing agriculture in the island. Today, at least 70% of the water from these irrigation canals is diverted to the Puerto Rico Aqueduct and Sewer Authority (PRASA) for residential and public use (Molina-Rivera, 2005, Distrito de Riego Guayama, 2010, Kuniansky and Rodríguez, 2010). The high diversions to PRASA are the result of the land use changes, substitution of extensive sugarcane agriculture for concentrated horticulture crops and the lack of water resources development for potable water supplies.

General concern for the conditions of the irrigation canals and the land surrounding them has increased in recent years. The Senate of Puerto Rico, in a project proposed by Fas Alzamora (2009), ordered the Agriculture Commission from the Senate of Puerto Rico and the Puerto Rico Department of Natural and Environmental Resources to perform exhaustive research on the state of the Irrigation Water Distribution Systems of Puerto Rico. Manuel Pacheco, Chief Engineer of the South Coast Irrigation District (personal communication, 2010) has publicly expressed great concern for the use and management of the land surrounding the canals. Concern for the state and well being of the irrigation canals is legitimate not just because of its importance as a source of water for agriculture and public supply but also because of the direct recharge that it induces into the shallow aquifer.

In the case of an increase in demand of irrigation water, as predicted by the Puerto Rico Water Resources and Environmental Research Institute (2005) and speculated by Fas Alzamora (2009), more than the current flow from the irrigation canals might be required for agricultural purposes. In recent years, the total water supplied from the reservoirs to these canals has decreased because of a decrease in irrigation water demands due to the considerable decrease in cultivated land along with lacking canal maintenance from PREPA. The change from the generally inefficient furrow irrigation used in sugarcane fields to the more efficient sprinkler and drip irrigation systems used in horticultural fields itself also has caused a considerable decrease in irrigation water deliveries to farmland.

The implementation of more efficient irrigation systems certainly is good for the coexistence of agriculture and development but not favorable for aquifer recharge. The more efficient irrigations systems aim to apply just enough water for the crop to satisfy the evapotranspiration needs, which tends to induce little deep percolation and aquifer recharge. Conversely, the gravity irrigation systems (flood and furrow) tend to apply excess water to the crops where the non evapotranspired water infiltrates through the soil, resulting in deep percolation, recharging the groundwater, and indirectly preventing excess salt accumulation in the productive soil profile. In other words, the more efficient irrigations systems permanently export the irrigation water out of the watershed through evapotranspiration and gravity irrigation systems keep a portion of the irrigation water in the aquifer under the watershed.

1.3 Irrigation in the Salinas to Patillas Area

The historical changes in water resources development and agricultural practices in the Salinas to Patillas area is representative of the entire South Coastal Plain (Kuniansky and Rodríguez, 2010). The hydrology of the South Coast aquifer has been progressively modified from its pre-developed state in the early 1800s, when the first diversion canals were constructed to redirect flow from large and convenient streams to irrigate sugarcane fields (Gómez-Gómez, 1991). The most drastic changes in the Salinas to Patillas area occurred between 1910 and 1935 after the Irrigation Canals Law passed in 1907 facilitating the construction of the Patillas-Guamaní canal in 1917. This happened in accordance with sugarcane cultivation expansion and with the introduction of electrical pumps in the early 1930s (Kuniansky and Rodríguez, 2010). The increase in irrigation for sugarcane production during these years caused groundwater withdrawals to peak at 310,000 m^3/day in 1947 along the South Coastal Plain and average between 114,000 and 220,000 m^3/day until the 1970s (Gómez-Gómez, 1991). After 1947, surface-water diversions began to decline as groundwater substituted for it in some areas. Sugarcane acreage began declining after 1970, followed by an increase in groundwater use for drip irrigation of horticultural crops in the mid and late 1970s, until the disappearance of the sugarcane industry in 1993 (Kuniansky and Rodríguez, 2010, Quiñones-Aponte *et al.*, 1997).

After the mid 1970s petrochemical and pharmaceutical industries were established in the Guayama area and replaced sugarcane as the main source of economic activity (Kuniansky and Rodríguez, 2010). In the 1980s, sugarcane production continued to decrease until reaching a critical low point in 1986 and eventually disappearing in 1993. In the early 1990s, agricultural activity diversified increasing production of horticultural crops, farinaceous and vegetable grew steadily until reaching its maximum in the early 2000s (Rodríguez, 2006) keeping a relatively steady production until 2005.

In the early and mid 1990s, the low water requirement of drip irrigation and the decrease in agricultural land resulted in substantially lower surface water deliveries from the Patillas-Guamaní canals (Table 1) (Quiñones-Aponte *et al.*, 1997, Rodríguez, 2006, Guayama Irrigation District, 2010). This translated to a reduction in the agricultural land that benefited from the Patillas-Guamaní canals from 4,050 ha in the 1980s to 600 ha in 2000s. These reductions caused PRASA to use the surplus water for public water supply. Additionally, the relatively recent reduction in water delivery through the irrigation canals can be attributed to the large portion of agricultural land that was subdivided into smaller farms, some of which have since been used for urban and suburban development or left fallow (Kuniansky and Rodríguez, 2010).

Table 1. Range of water deliveries in the Patillas-Guamaní irrigation canals. [1]

Period	**Water deliveries (m^3/year)**
Prior to 1980s	57,000,000 to 110,000,000
Early 1980's	27,100,000 to 49,300,000
Early 1990's	12,300,000 to 21,000,000
Early 2000's	7,400,000 to 11,100,000

According to Manuel Pacheco (personal communication, 2010), during the year 1998 irrigation water deliveries from the Patillas-Guamaní canals further decreased due to damages in the final section of the Patillas canal that were never repaired. This section is the cross over to the Río Salinas (also called Río Nigua de Salinas) which provided water to a significant agricultural area in the Salinas municipality. As a result, in recent years the canals mostly served agricultural water to the eastern part of the Salinas municipality and to the municipalities of Guayama, Arroyo and Patillas, where farmers in the mid and western Salinas area either pumped groundwater or obtained water from the Juana Díaz canal with some transporting water over the Río Nigua de Salinas from the Patillas-Guamaní canals.

Even though groundwater withdrawals have decreased since the 1970s within the study area, the potentiometric surface in coastal portions of the aquifer has been lowered because of the reduced irrigation return flow to the aquifer as indicated by the cones of depression delineated by Rodríguez (2002 and 2006).

1 - Guayama Irrigation District (2010)

Today, between 30% and 45% of the active agricultural land in the study area is solely used to cultivate plantains and bananas (Manuel Díaz-Rivera, Agricultural Extension Service Farinaceous Expert and Franklyn Román, Agricultural Extension Service Agronomist for the municipality of Patillas, personal communication 2010). Plantains and bananas represented the most important agricultural crop on the island (FAO STATS, 2008; Departamento de Agricultura, 2010). For example, during the year 2002 in the Salinas municipality 310 ha were dedicated to plantains, 235 ha to bananas and 190 ha to grains, 150 ha to vegetables, while 630 ha were in pastures and other crops (USDA Agricultural Census, 2002).

Therefore, the overall objective of this project is to develop a water balance of the Patillas-Salinas coastal watersheds subject to intensive agricultural practices and served by two irrigation canals and groundwater supply. Specific objectives of the project are:

a. to develop a model for understanding and explaining changes in aquifer piezometric levels that takes into account land use changes and changes in irrigation water supplies,
b. propose alternatives for improving aquifer recharge from irrigation water excess.

2. Description of the Study Area

The Patillas-Guamaní irrigation water conveyances represent an important and extensive arrangement of canals. To illustrate its location and extension, the Patillas-Guamaní irrigation influence area, water conveyances layout and original map are presented in Figures 1, 2 and 3, respectively, and the length of its mains and laterals are presented in Tables 2 and 3. The Patillas canal runs west from the municipality of Patillas towards Salinas and the Guamaní canal runs west from the municipality of Guayama towards Salinas but north of the Patillas canal. A lateral of the Guamaní canal used to run east from Guayama towards Patillas but it was damaged in the early 1990s. The section of the Guamaní canal that used to run east is generally called East Guamaní canal while the section that runs west is called the Guamaní canal.

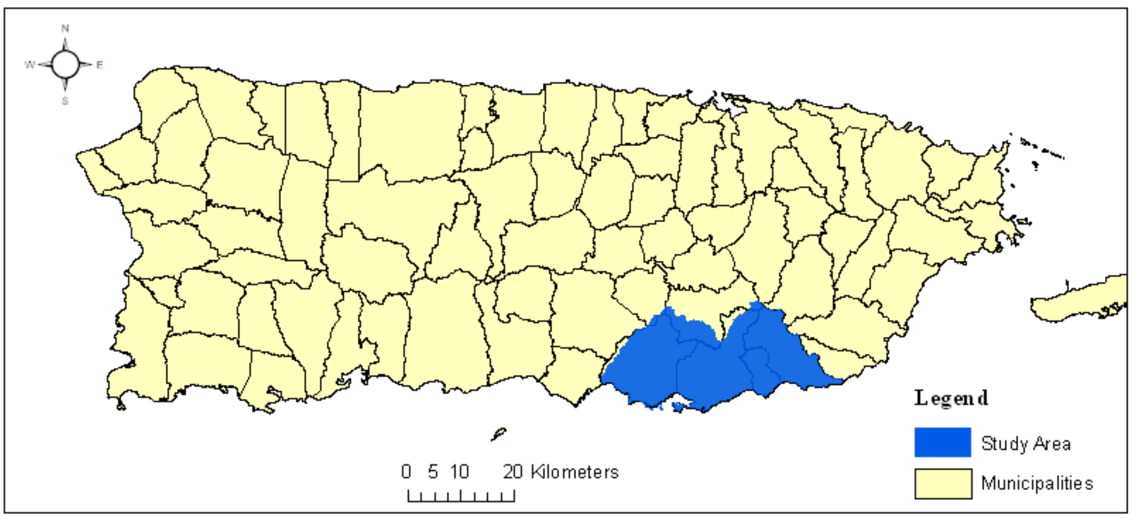

Figure 1. Salinas to Patillas study area, located in the Southeast of Puerto Rico.

Table 2. Original coverage of the Guayama District irrigation system. [2]

Section	Length (m)
Patillas Canal Main	40,381
Patillas Canal Laterals	30,940
West Guamaní Canal Main	22,474
West Guamaní Canal Laterals	12,303
East Guamaní Canal Main	6,402
East Guamaní Canal Laterals	854
Total Length	113,354

2 - Guayama Irrigation District (2010)

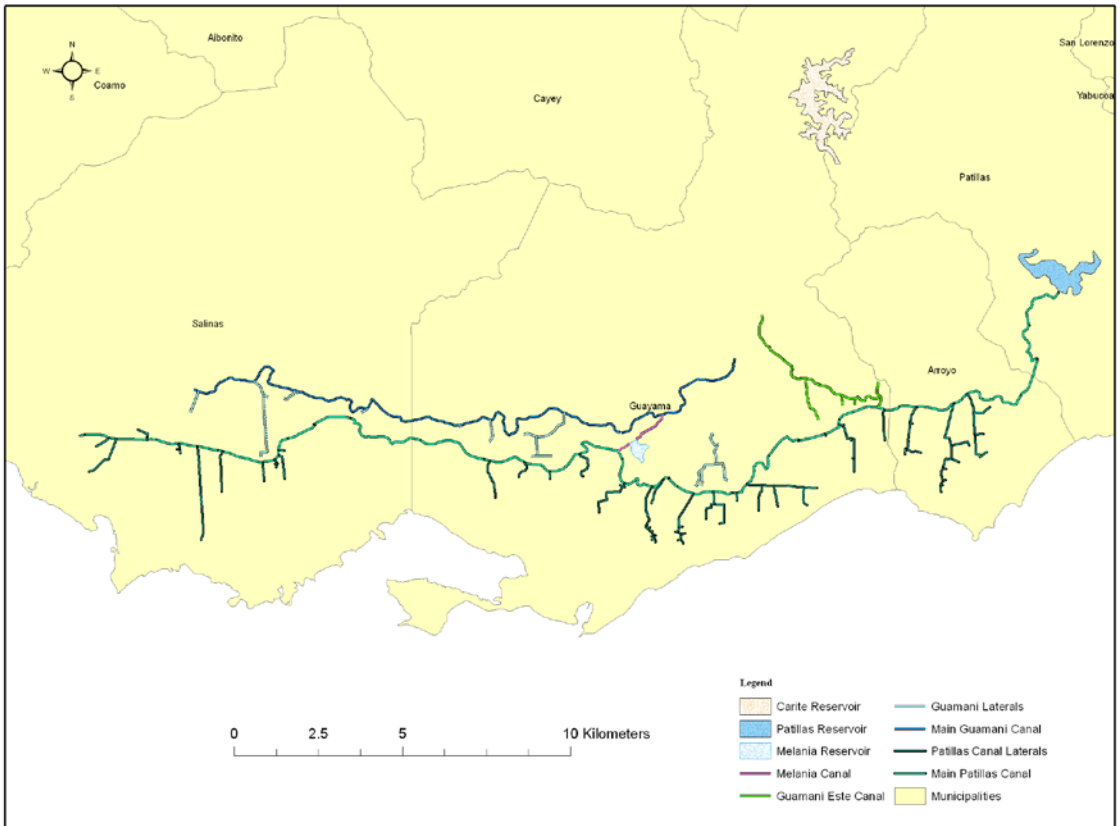

Figure 2. Layout of the Patillas-Guamaní Irrigation Canals. [3]

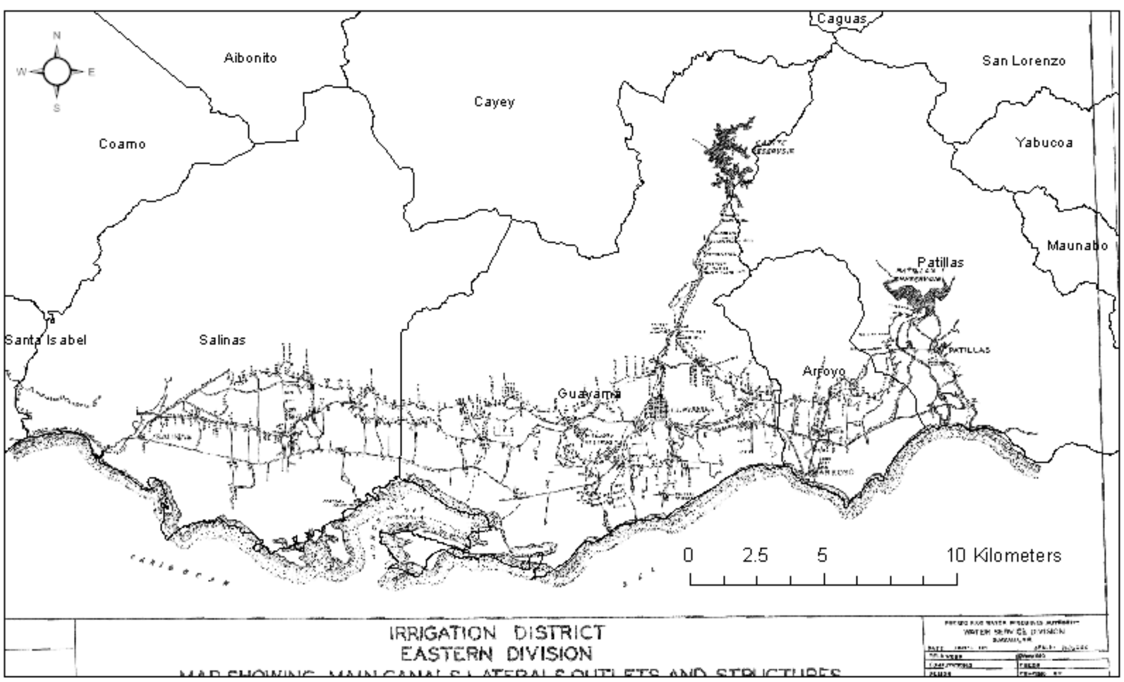

Figure 3. Original map of the Patillas-Guamaní canals. [4]

3 - Irizarry (2010)

Table 3. Guayama District irrigation system individual laterals length.[5]

Patillas Canal		**East Guamaní Canal**		**West Guamaní Canal**	
Lateral	**Length (m)**	**Lateral**	**Length (m)**	**Lateral**	**Length (m)**
P-31	3,139	GE-12	61	G-1	1,372
P-32	3,444	GE-14	259	G-1-A	3,729
P-36	2,077	GE-16	76	G-14	2,460
P-40	697	GE-21	457	G-22	6,10
P-47	1,392	G-24	61		
P-50	3,004	G-36	510		
P-52	136	G-40	2,858		
P-55-1/2	1,488	G-44	698		
P-59	816				
P-60	3,074				
P-63	1,189				
P-68	481				
P-72	175				
P-74	602				
P-76-1/2	1,179				
P-77	3				
P-98	61				
P-100	91				
P-104	716				
P-110	1,250				
P-112-1/2	2,187				
P-116	61				
P-124	1,226				
P-125	258				

The Salinas to Patillas study area represents 38% of the total area influencing the South Coast Aquifer; Figure 4 presents the southern Puerto Rico watersheds that are believed to influence the South Coast Aquifer. The watersheds under study are bordered to the north by the foothills of the Cordillera Central in the Aibonito, Cayey and San Lorenzo area, to the south by the Caribbean Sea, to the west by the Río Majada basin in Salinas (Figure 5), and to the east by Río Grande de Patillas basin in Patillas. The Río Majada basin is constituted by the Río Jajome, Río Lapa, Río Majada and Río Salinas. The watersheds over the aquifers under study (Figure 6) consist of 53,100 ha (531 km^2) within the municipalities of Salinas, Guayama, Arroyo, Cayey and Patillas; this is about 6% of the total surface area of Puerto Rico. These watersheds are located mostly over a coastal alluvial plain which is the major geographic feature within the Salinas to Patillas

4 - Guayama Irrigation District (2010) in Irizarry (2010)

5 - Guayama Irrigation District (2010)

region, and are a major source of water for agricultural irrigation, public, industrial and domestic water supply (Molina-Rivera, 2005).

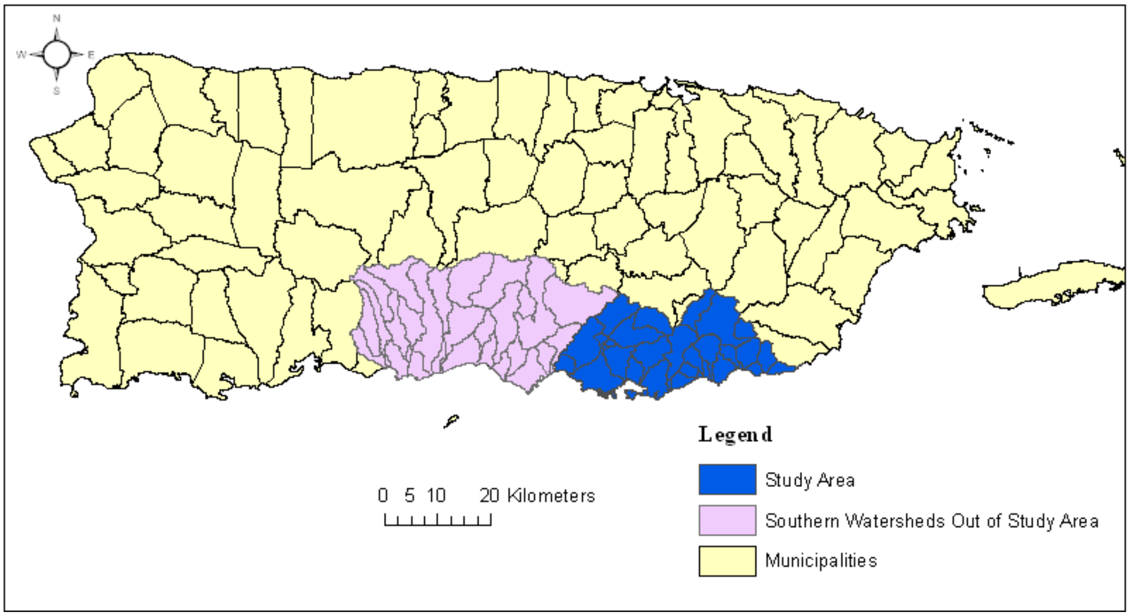

Figure 4. Puerto Rico South Coast Aquifer and aquifers within the study area.

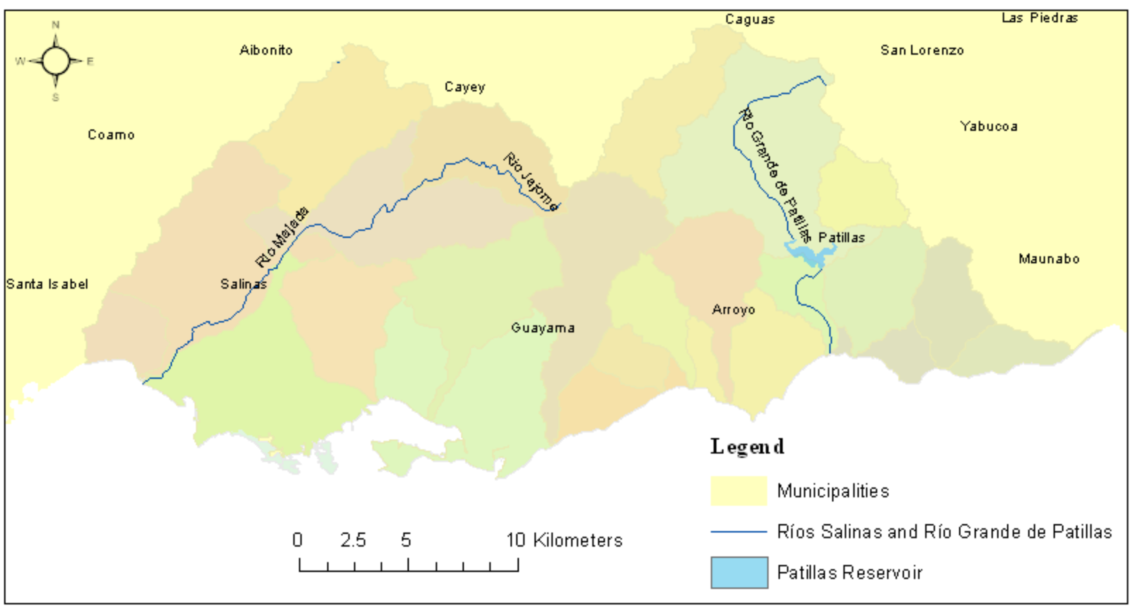

Figure 5. Río Majada and Río Grande de Patillas basins.

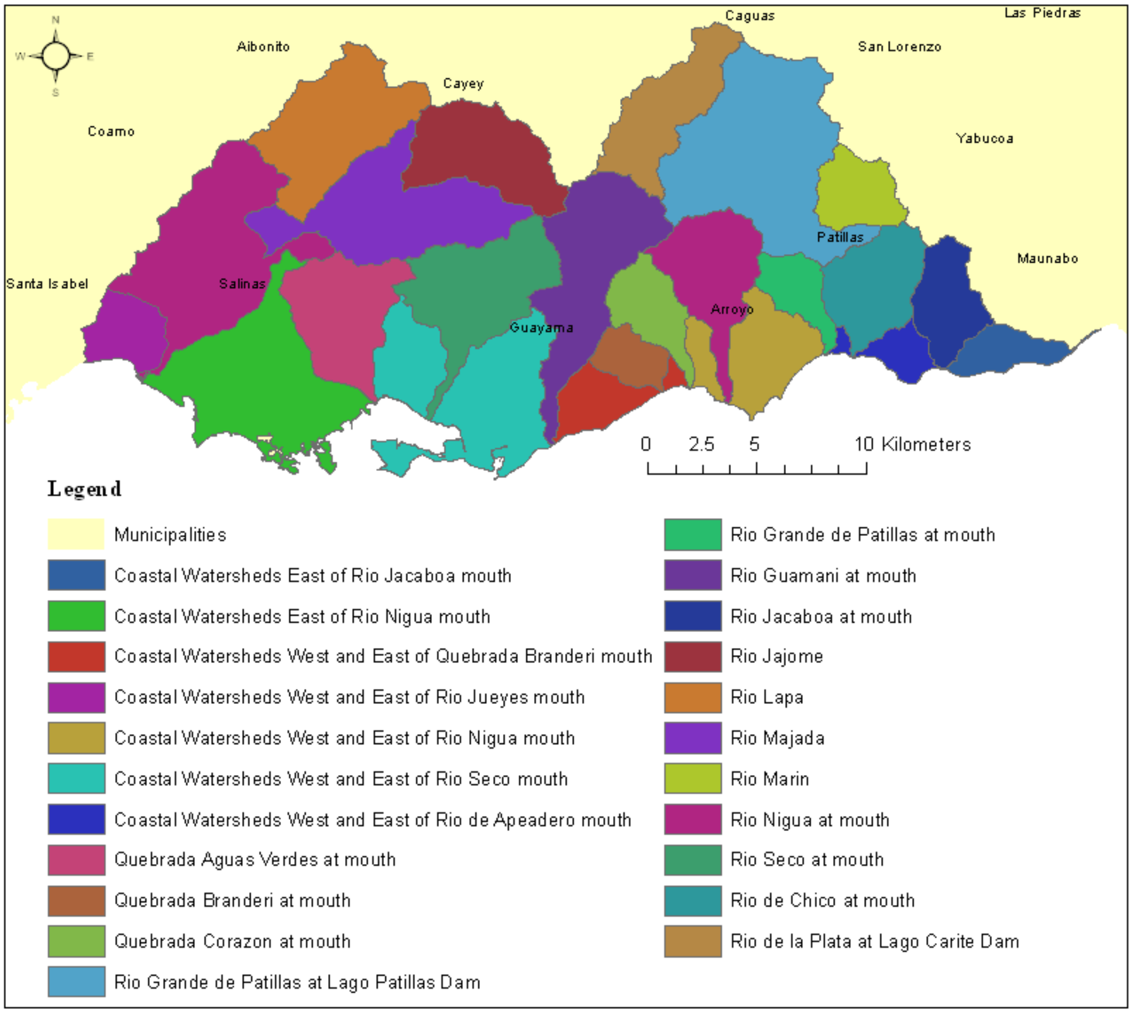

Figure 6. Study area surface watersheds.

Elevation within the Salinas to Patillas area changes from sea level on the coast to 1,336 m at the highest point of the Carite Reservoir watershed. The Carite Reservoir watershed is part of Río La Plata basin, which contrary to all other hydrological features within the study area, flows northward. Originally not included as a watershed of influence to the South Coast Aquifer, the Carite Reservoir watershed was added; in limited extend, to the water balance estimation process because the Carite Dam in the Carite Reservoir when necessary provides water transfers to Río Guamaní and eventually to the Guamaní irrigation canal.

Geographically, the Salinas to Patillas region described here is divided into two major parts. The northern part is characterized by steep-sloped high elevation mountainous areas. The alluvial/agricultural valleys in the southern section are at elevations bellow 64 m (Figure 7) and are characterized by gentle slopes (Figure 8). Based on maps published by Ramos and Lugo (1994) and by Kennaway and Helmer, (2007), almost all irrigated agriculture occurs at elevations of 64 m or lower with slopes between 0 and 5 %, where soils are deep and well drained, there is good plant-water availability, and irrigation canals are available. Because of these attributes, this area was one of the richest agricultural areas on the island, and still has high agricultural potential.

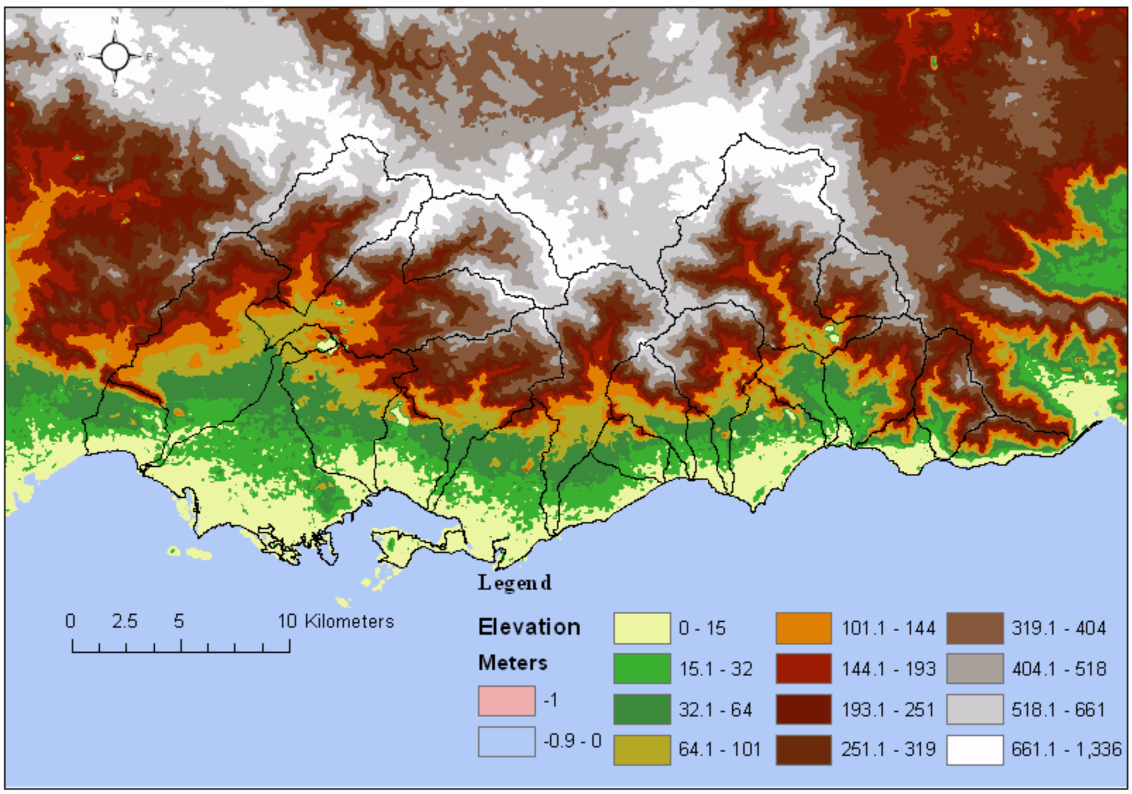

Figure 7. Elevation map of the Salinas to Patillas study area.

The geology of the Salinas to Patillas region and its surroundings consists of three basic lithologic units shown in Figure 9. These are the volcanic-volcaniclastic rocks, the Juana Díaz Formation of the Oligocene age, and the alluvial deposits (Ramos Ginés, 1994c). The alluvial deposits are hydrogeologically the most important lithologic unit in the area (Ramos Ginés, 1994c) and over this area is where most of the local agriculture takes place. These deposits are composed of layers of unconsolidated to poorly consolidated clay, sand, gravel, and boulders (Ramos Ginés, 1994c).

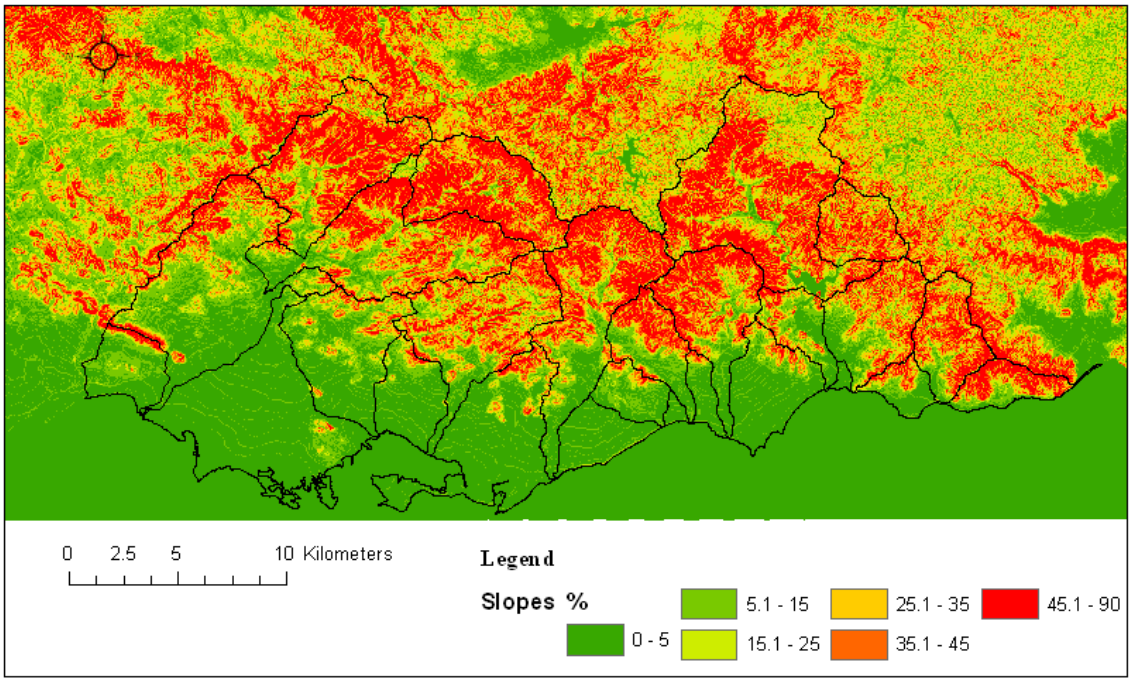

Figure 8. Slope map of the Salinas to Patillas study area.

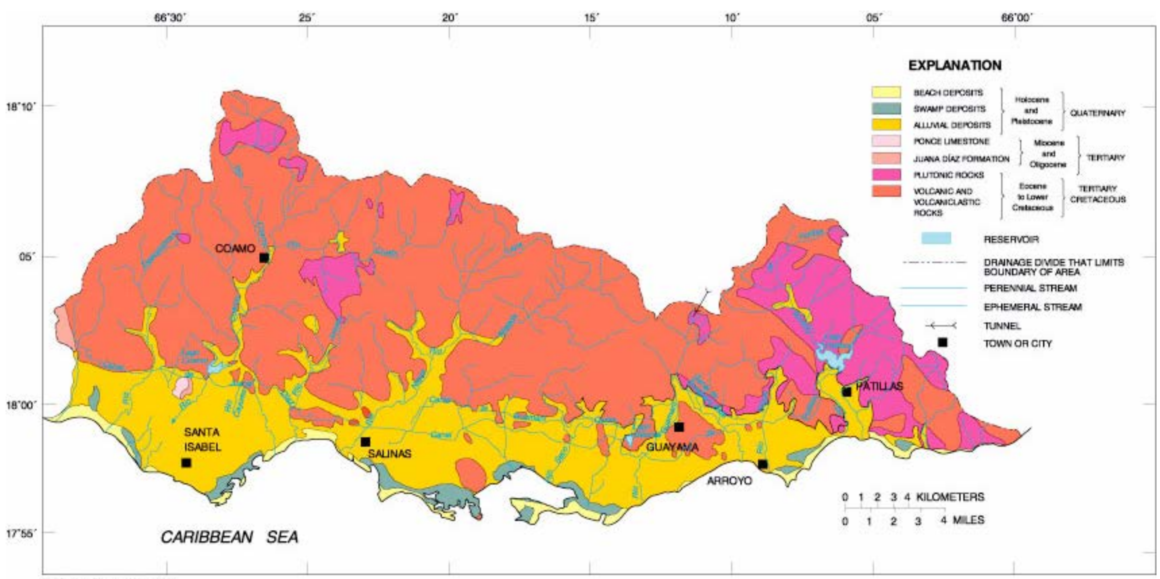

Figure 9. Geological formations within the study area and its surroundings. [6]

The alluvium in the Salinas to Patillas area contains the only sizeable aquifer (Ramos Ginés, 1994c). This aquifer is composed of fan-delta, interfan, and alluvial valley deposits (Gómez-Gómez, 1987, 1991; Renken *et al.*, 2002) which, in Figure 10, are

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6 - Modified from Briggs and Akers (1965); found on Ramos Ginés (1994c)

referred to as intergranulate aquifers. This aquifer is generally under water table conditions and has an aquifer thickness ranging from zero at the edge of the bedrock-alluvial contact to about a 1,000 m in the vicinity of Santa Isabel (Ramos Ginés, 1994c). The aquifers in the fractured volcanic and plutonic rocks sustain very low yields (Ramos Ginés, 1994c). Near the coastline, the study area is characterized by the presence of public beaches, mangrove swamps, coastal lagoons, and salt and tidal flats (Kuniansky and Rodríguez, 2010).

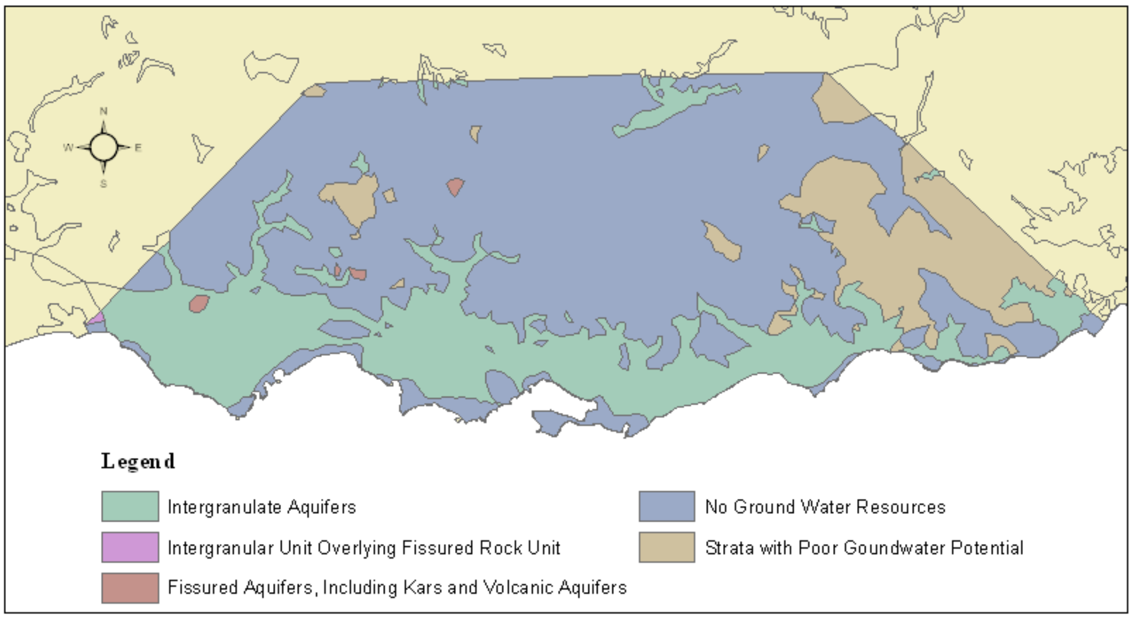

Figure 10. Aquifers within the study area and its surroundings.

Groundwater levels in the Salinas to Patillas region range from 50 to 70 m above mean sea level near the bedrock-alluvial contact to a meter or so above mean sea level near the coast (Ramos Ginés, 1994c). Groundwater levels may fluctuate as much as 3 m as a result of seasonal changes (Ramos Ginés, 1994c) between draught and rainy periods, where groundwater tends to move seaward as shown in Figure 11. Within the study area, the drought period (precipitation bellow 100 mm/mo) is considered from December through April and the rainy period (over 100 mm/mo) from May through November.

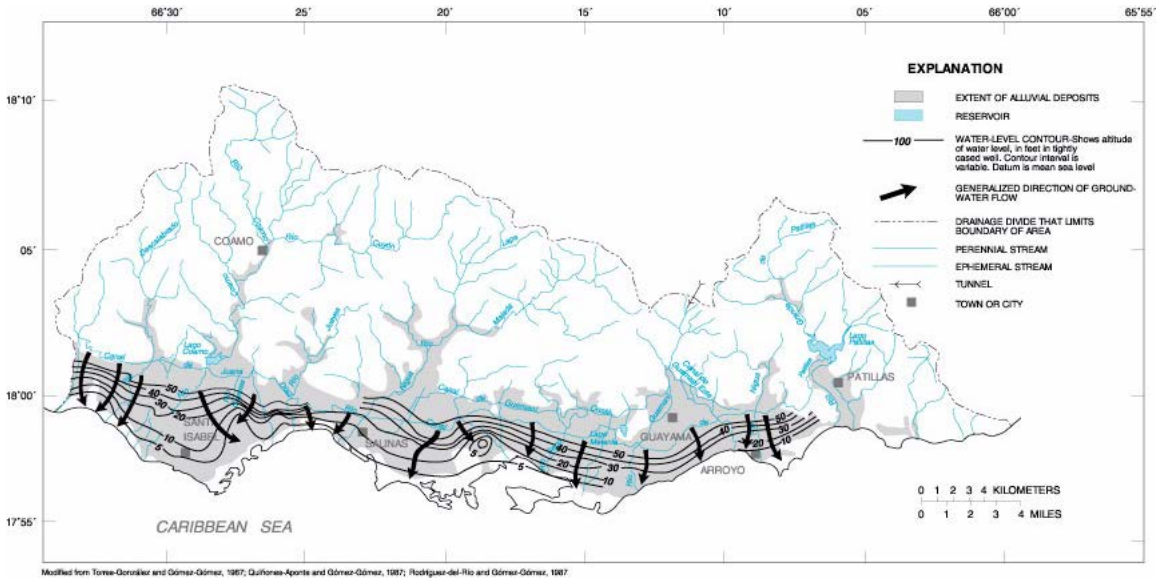

Figure 11. Altitude of water level surface and direction of groundwater during 1986 and 1987 in the Santa Isabel-Patillas region. [7]

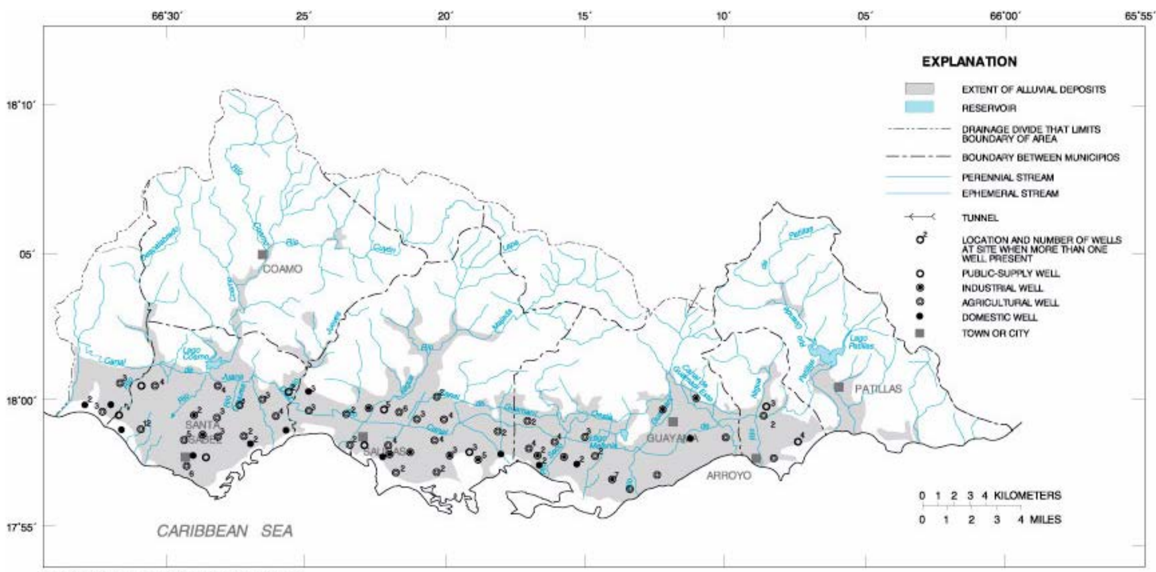

Figure 12. Approximate well locations in the Santa Isabel-Patillas region. [8]

Most wells within the study area extract water from the water table aquifer for five purposes: agriculture, industrial parks, public supply, thermoelectric processes and domestic supply at much smaller scale than the first four purposes. Figure 12 shows the approximate well locations for the late 1980s. Out of the approximately 106 wells in the

7 - From Torres-González, and Gómez-Gómez (1987), found on Ramos Ginés (1994c)

8 - U.S. Ground Water Site Database (1991), found on Ramos Ginés (1994c)

Salinas to Patillas area in the late 1980s, about 48 of them were dedicated to agricultural purposes (Table 4) (U.S. Geological Survey Ground Water Site Database, 1991, found on Ramos Ginés, 1994c). Pumping rates varied greatly depending on the purpose of extraction and area. Water extraction rates are shown in Figures 13, 14, 15 and 16 for the different municipalities for different years while Table 5 show the lumped extraction rates as estimated in several publications by the USGS.

While in Arroyo, Guayama and Patillas the number of agricultural wells considerably decreased after sugarcane production ended, the amount of wells remained relatively steady in Salinas, as shown in Table 4. This can be attributed to two factors: compared to the other three municipalities, Salinas quickly experienced an aggressive change from sugarcane to horticultural crops in the 1980s and 1990s (Kuniansky and Rodríguez, 2010), and water deliveries from the Patillas-Guamaní canals to Salinas decreased after the rupture of the connection over the Río Salinas (Río Nigua de Salinas) in 1998 (Manuel Pacheco, Personal Comm., 2010). Nonetheless, total well water extractions and extraction rates depleted considerably in all four municipalities as shown in Figures 13, 14, 15 and 16 and Table 5. Where in Figures 13 through 16 are presented the reported groundwater pumpage distribution shown in Table 5.

Table 4. Irrigation water wells in the Salinas to Patillas area. [9]

Year	**Arroyo**	**Guayama**	**Patillas**	**Salinas**	**Total**
1987	6	9	11	22	48
1993	0	4	4	20	28
1998	0	5	2	11	18
2002	0	2	7	21	30
2007	0	3	3	22	28

9 - USDA Agricultural Census, 1994; 2000; 2004; 2009

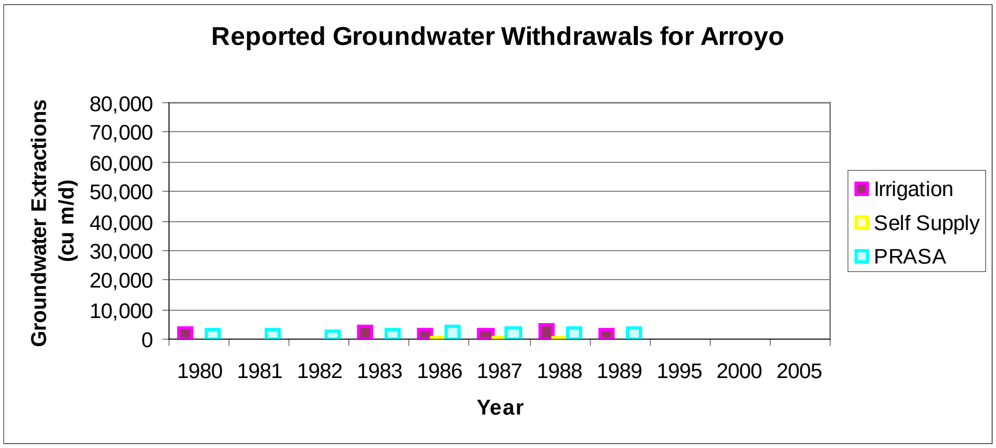

Figure 13. Estimated groundwater withdrawals for the Arroyo municipality. [10]

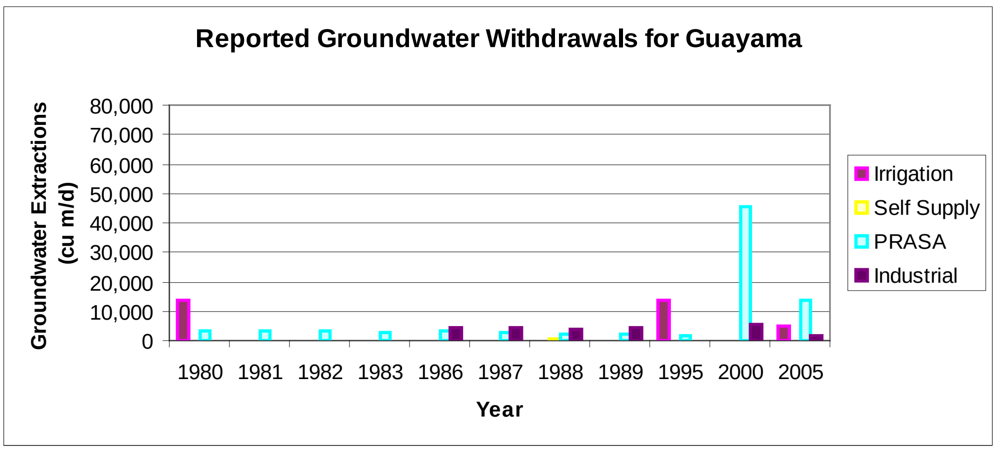

Figure 14. Estimated groundwater withdrawals for the Guayama municipality. [10]

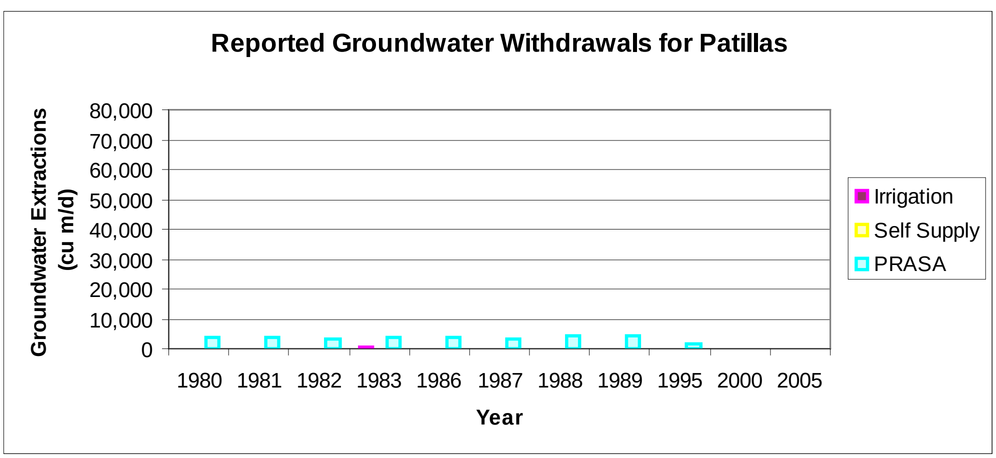

Figure 15. Estimated groundwater withdrawals for the Patillas municipality. [10]

10 - Torres-Sierra and Avilés, 1986; Ramos Ginés, 1994c; Molina-Rivera and Dopazo, 1995; Dopazo and Molina-Rivera, 1995; Molina-Rivera, 1998; Molina-Rivera, 2005; Molina-Rivera and Gómez-Gómez, 2008. See Table 5

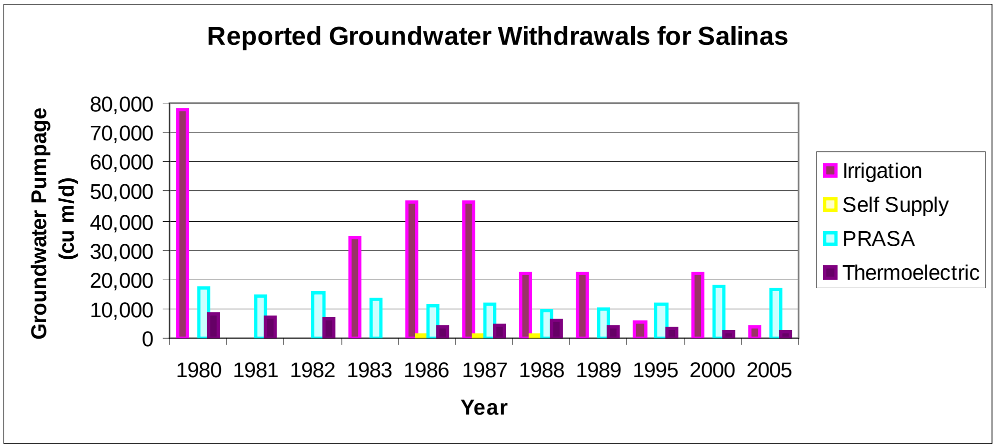

Figure 16. Estimated groundwater withdrawals for the Salinas municipality. [10]

Table 5. Estimated rate of groundwater withdrawals (m^3/day) during the study period. [11]

Year	Arroyo	Guayama	Patillas	Salinas	Total
1980[a]	7230	16921	3937	103001	131089
1981[a]	7610	14681	3773	85387	111450
1982[a]	7118	12176	3495	71407	94197
1983[b]	7955	9558	4125	53124	74763
1986[c]	8290	7647	3520	61929	81386
1987[c]	7760	7344	3331	63330	81765
1988[d]	9085	7154	4505	38952	59696
1989[d]	7419	6965	4202	35886	54472
1995[e]	0	15331	1741	20063	37135
2000[f]	0	50762	0	41905	92667
2005[g]	0	20176	0	23356	43532

Along with changes in surface water deliveries and groundwater extractions for agricultural purposes, irrigation systems also changed, experiencing a metamorphosis from gravity systems to sprinkler and/or drip irrigation systems. Even though there was no available data of the amount and distribution of irrigation systems prior to 1998, it is common knowledge that gravity systems were predominant in the area prior to the year 1990. Table 6 presents data obtained by the USDA Agricultural Census for the last 3 census surveys which shows the end of this metamorphosis.

11 - Reported in publications by: aTorres-Sierra and Avilés, 1986; bRamos Ginés, 1994c; cMolina-Rivera and Dopazo, 1995; dDopazo and Molina-Rivera, 1995; eMolina-Rivera, 1998; fMolina-Rivera, 2005; gMolina-Rivera and Gómez-Gómez, 2008

Table 6. Irrigation systems distribution in the Salinas to Patillas area. [12]

Year	Arroyo	Guayama	Patillas	Salinas	Total
1998	7G	2G, 4D, 1S	2G, 1S	4G, 8D, 1S	30
2002	3 G	3D, 1O	1G, 5D, 3S	1G, 21D, 2S, 1O	41
2007	0	1G, 3D, 1S, 1O	3G, 3D	4G, 19D, 2S	37

G = Gravity (furrow, flood), D= Drip (micro irrigation, trickle), S= Sprinkler, O= Other (center pivot, underground)

From data published by the Agricultural Census in the various publications for Puerto Rico it can be inferred that some irrigation water is obtained from rivers and streams within the study area although this is not assessed in this model. The major streams within the study area are mentioned in Table 7 and all water bodies are presented in Figure 17. Apart from the irrigation canals, streams present in the area of interest are intermittent, losing their entire flow through seepage to the aquifer in their middle and upper reaches, and none of them flow across the entire coastal plain except shortly after rainfall-runoff events (Kuniansky and Rodríguez, 2010).

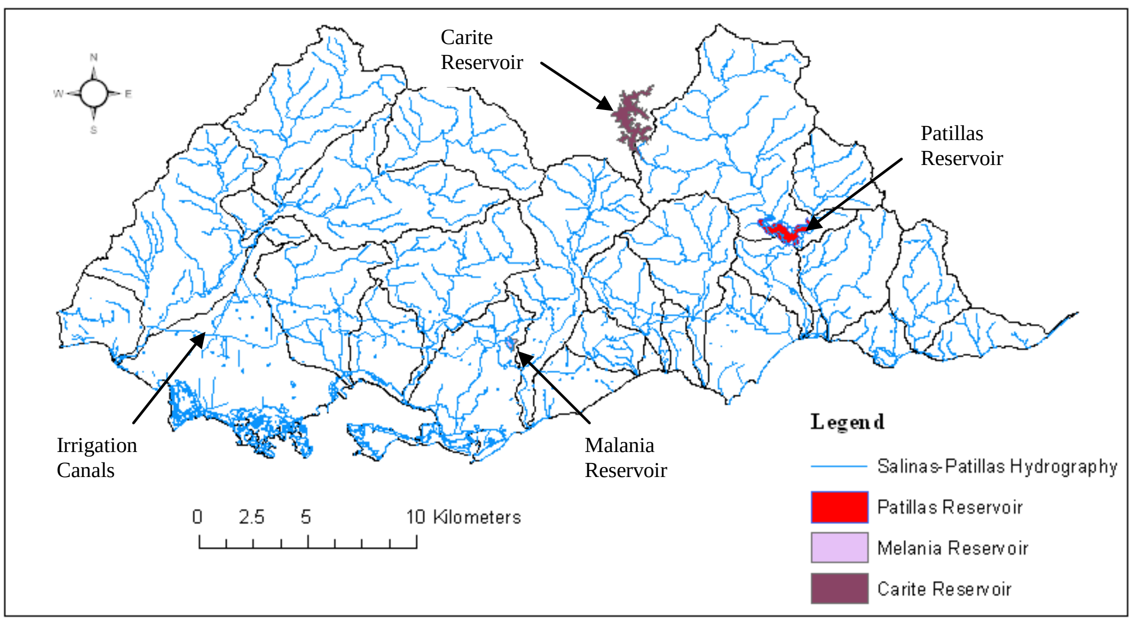

Figure 17. Streams and reservoirs within the Salinas to Patillas study area.

12 - USDA Agricultural Census (2000; 2004; 2009)

Table 7. Main water bodies within the study area.

Water body/Watershed	**Water body/Watershed**
Patillas-Guamaní canals	Río Seco
Río Salinas	Río Nigua de Arroyo
Río Lapa	Río Chico
Río Jájome	Río Jacaboa
Río Majada	Quebrada Corazón
Río Marin	Quebrada Aguas Verdes
Río Guamaní	Quebrada Branderi

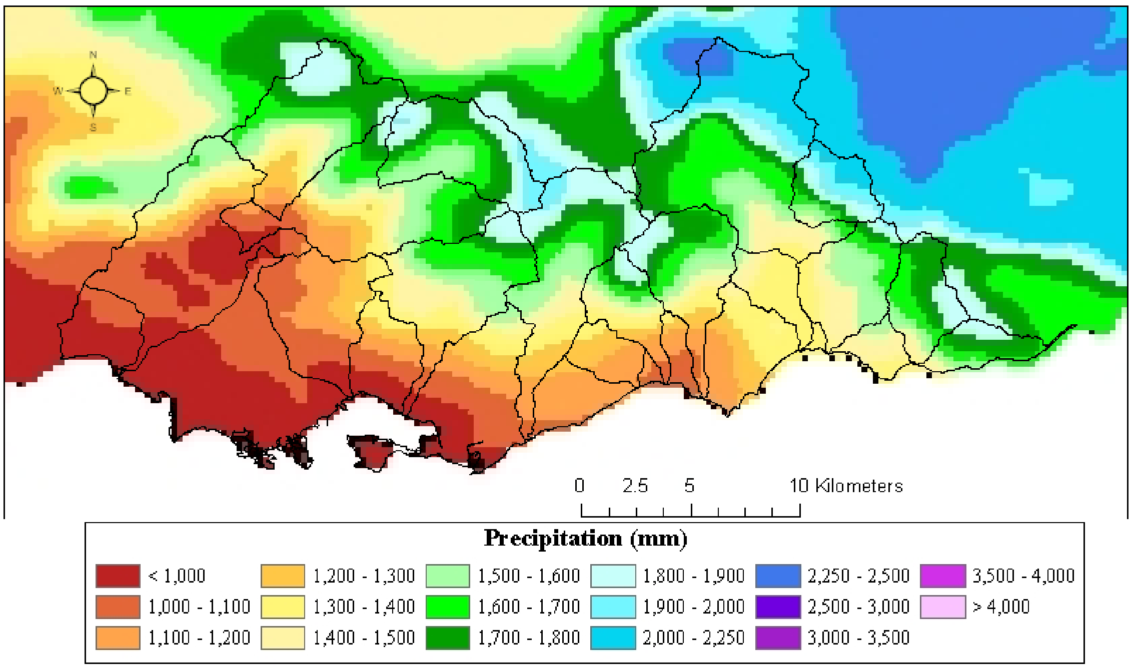

Figure 18. PRISM thirty year average precipitation distribution in Puerto Rico. [13]

Rainfall-runoff events within the area of interest do not occur as often as in most parts of the island because of the amount and frequency of precipitation and the soil characteristics. Characteristics that support low precipitation-runoff events include high infiltration rates and high hydraulic conductivity (Ramos Ginés, 1994c), high soil storage capacity and thickness, good soil drainage and relatively low impermeable areas. Average annual precipitation in the agricultural area is less than 1200 mm/yr (Figure 18) while evapotranspiration typically is over 1200 mm/yr according to preliminary studies using Harmsen's PR-ET (2002) computer model for a general crop. This agricultural water deficit has been well documented by McClymonds and Díaz (1972), Capiel and

13 - Oregon state University Station Climate Analysis Service (2002)

Calvesbert (1976), Bennett (1976), Heisel and González (1979), Larsen and Concepcion (1998), Atkins *et al.* (1999), Department of Natural Resources and Environment (2005), Kuniansky *et al.* (2004) and Kuniansky and Rodríguez (2010).

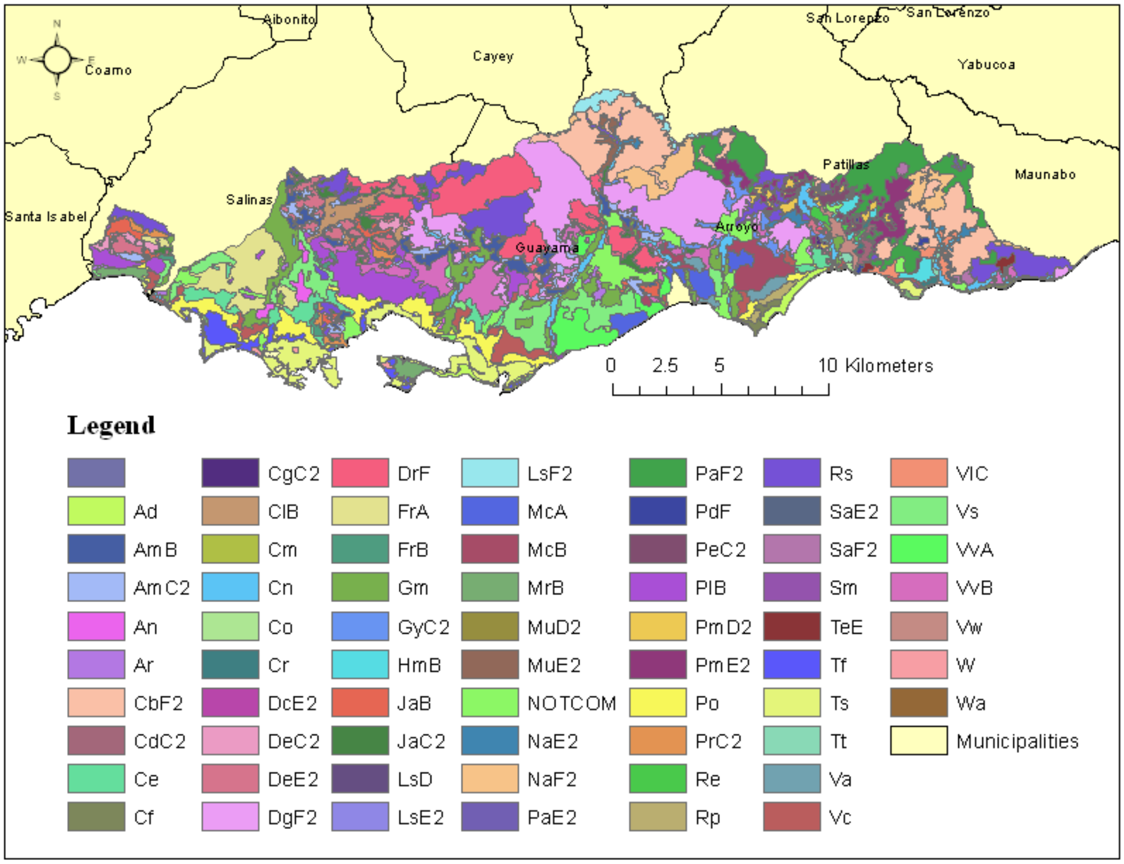

Figure 19. Soils within the agricultural area of interest. [14]

Soils in the agricultural area of interest (Figure19) are deep with a weighed average depth of 1050 mm and a relatively high soil water availability for plants with a weighed average water depth of 10.84 cm/100cm as derived from spatial analysis of data from the USDA Natural Resources Conservation Service (NRCS) Soil Data Mart. The vast majority are well drained, but erodible soils. Tables 8 and 9 present the soils, fraction of cover and hydrologic group for each soil mapping units in the agricultural area of, interest. Hydrologic group A represents soils with the higher infiltration capacity (saturated hydraulic conductivity >36 mm/hr) and hydrologic group D represents soils

14 - USDA-NRCS Soil Data Mart

with the lower infiltration capacity (saturated hydraulic conductivity <1.5 mm/hr) B and C groups represent soils with moderate high (saturated hydraulic conductivity from 15 to 36 mm/hr) and moderate low (saturated hydraulic conductivity from 1.5 to 15 mm/hr) infiltration capacity (USDA-NRCS, 1997), respectively. Also, several of these soils are classified as prime farmland soils and farmland soils of statewide importance which are the highest classification the NRCS gives to agricultural soils relative to their importance.

In the current study, special emphasis is given to the surface/groundwater interactions related to the farmland around the Canal de Patillas and Canal de Guamaní (Figure 2 and 3) due to their historical importance and agriculture potential as a major source of irrigation water. Also, even though the sources of aquifer recharge may vary throughout the region, seepage from rivers and irrigation canals represents a major source of groundwater recharge (Ramos Ginés, 1994c) in the Salinas to Patillas area. Although aquifer recharge from stream flow has been well documented, recharge from irrigation water conveyance losses from water diverted from Lago Carite and Lago Patillas through the Canal de Guamaní and Canal de Patillas (Ramos Ginés, 1994c) have not.

For different reasons such as urbanization, groundwater pumpage and marine ecology, there is a latent concern for the status, use and management of the farmland around the irrigation canals, on the irrigation canals themselves and the water they deliver. For example, through analysis done by Torres-González and Gómez-Gómez (1987), Kuniansky *et al*, (2004), and Kuniansky and Rodríguez (2010), and confirmed in the current study, it is very likely that if diversion from reservoirs to irrigation canals and then to farms ceases and actual groundwater pumpage is sustained, the aquifer will undergo an abrupt decrease in water levels. On the other hand, farmland that is developed into infrastructure, residential or commercial uses is lost forever reducing even further opportunities for aquifer recharge.

Table 8. Soils within the irrigated watersheds.[15]

Symbol	Hydraulic Class	% of total area	Soil
Ad	A	0.62	Aguadilla loamy sand
AmB	C	1.79	Amelia gravelly clay loam, 2 to 5 percent slopes
AmC2	C	2.11	Amelia gravelly clay loam, 5 to 12 percent slopes, eroded
An	A	0.45	Arenales sandy loam
Ar	A	0.35	Arenales sandy loam, gravelly substratum
CbF2	D	7.35	Caguabo clay loam, 20 to 60 percent slopes, eroded
CdC2	C	0.20	Candelero loam, 5 to 12 percent slopes, eroded
Ce	D	1.92	Cartagena clay
Cf	A	0.44	Cataño loamy sand
CgC2	C	0.06	Cayagua sandy loam, 5 to 12 percent slopes, eroded
ClB	C	0.86	Coamo clay loam, 2 to 5 percent slopes
Cm	D	0.22	Coastal beaches
Cn	A	2.01	Cobbly alluvial land
Co	D	0.03	Coloso silty clay loam, occasionally flooded
Cr	D	0.17	Coloso silty clay
DcE2	C	0.04	Daguao clay, 20 to 40 percent slopes, eroded
DeC2	D	0.66	Descalabrado clay loam, 5 to 12 percent slopes, eroded
DeE2	D	2.02	Descalabrado clay loam, 20 to 40 percent slopes, eroded
DgF2	D	9.87	Descalabrado and Guayama soils, 20 to 60 percent slopes, eroded
DrF	D	6.17	Descalabrado-Rock land complex, 40 to 60 percent slopes
FrA	D	3.01	Fraternidad clay, 0 to 2 percent slopes
FrB	D	0.30	Fraternidad clay, 2 to 5 percent slopes
Gm	B	4.48	Guamaní silty clay loam
GyC2	B	1.09	Guayama clay loam, moderately deep variant, 2 to 12 percent, slopes, eroded
HmB	D	0.62	Humacao loam, 2 to 5 percent slopes
JaB	D	0.95	Jacana clay, 2 to 5 percent slopes
JaC2	D	1.46	Jacana clay, 5 to 12 percent slopes, eroded
LsD	C	0.01	Los Guineos silty clay loam, 12 to 20 percent slopes
LsE2	C	0.12	Los Guineos silty clay loam, 20 to 40 percent slopes, eroded
LsF	C	0.00	Los Guineos clay, 40 to 60 percent slopes
LsF2	C	0.62	Los Guineos silty clay loam, 40 to 60 percent slopes, eroded
McA	C	1.24	Machete loam, 0 to 2 percent slopes
McB	C	1.62	Machete loam, 2 to 5 percent slopes
MrB	A	0.91	Meros sand, 1 to 6 percent slopes
MuD2	D	0.02	Mucara silty clay loam, 12 to 20 percent slopes, eroded
MuE2	D	0.32	Mucara silty clay loam, 20 to 40 percent slopes, eroded
NaE2	C	0.51	Naranjito silty clay loam, 20 to 40 percent slopes, eroded
NaF2	C	2.23	Naranjito silty clay loam, 40 to 60 percent slopes, eroded
NOTCOM	D	3.32	Not Surveyed
PaE2	D	0.12	Pandura loam, 12 to 40 percent slopes, eroded
PaF2	D	4.94	Pandura loam, 40 to 60 percent slopes, eroded

15 - NRCS Soil Data Mart

Table 9. Soils within the irrigated watersheds (Cont.). [15]

Symbol	Hydraulic Class	% of total area	Soil
PdF	D	0.12	Pandura-Very stony land complex, 40 to 60 percent slopes
PeC2	D	0.64	Parcelas clay, 5 to 12 percent slopes, eroded
PlB	D	3.53	Paso Seco clay, 0 to 5 percent slopes
PmD2	B	0.61	Patillas clay loam, 12 to 20 percent slopes, eroded
PmE2	B	2.24	Patillas clay loam, 20 to 40 percent slopes, eroded
Po	D	3.23	Ponceña clay
PrC2	B	0.53	Pozo Blanco clay loam, 5 to 12 percent slopes, eroded
Re	A	0.22	Reilly soils
Rp	D	0.28	Reparada clay
Rs	D	5.50	Rock land
SaE2	D	0.09	Sabana silty clay loam, 20 to 40 percent slopes, eroded
SaF2	D	0.20	Sabana silty clay loam, 40 to 60 percent slopes, eroded
Sm	D	0.04	Salt water marsh
TeE	D	0.21	Teja gravelly sandy loam, 12 to 40 percent slopes
Tf	D	1.35	Tidal flats
Ts	D	3.56	Tidal swamp
Tt	B	0.16	Toa silty clay loam
Va	D	0.57	Vayas silty clay loam, occasionally flooded
Vc	D	1.69	Vayas silty clay, frequently flooded
VlC	B	0.49	Via silty clay loam, 3 to 10 percent slopes
Vs	D	3.93	Vives silty clay loam, high bottom
VvA	B	1.84	Vives clay, 0 to 2 percent slopes
VvB	B	3.15	Vives clay, 2 to 7 percent slopes
Vw	B	0.40	Vivi loam
Wa	D	0.03	Wet alluvial land
W		0.17	Water
Distribution Summary			
A	5 %		
B	16 %		
C	10 %		
D	69 %		

Furrow irrigation efficiency is about 65% compared to the 80% to 90% that can be achieved with micro irrigation (James, 1988). Also, sugarcane irrigation water requirements are higher than those for the farinaceous and vegetable crops that prevailed in the study area (based on data published by Allen, 1998). In other words, a huge amount of water was required to irrigate sugarcane under the conditions prior to the period between 1986 and 1993 compared to the currently used drip and sprinkler irrigation systems.

According to Kuniansky and Rodríguez (2010) freshwater and marine life has been affected by the changes in irrigation practices in the Salinas area due to the depletion in ground and surface water flows that furrow irrigation used to produce. The western watersheds of the study area drain towards the Jobos Bay National Estuary in the Jobos Bay Reserve. For about 70 years this estuary received considerable stream and groundwater flow generated by the flood and furrow irrigation in the area. Obviously, this flow did not exist prior to the establishment of the Patillas-Guamaní canal in 1917 and it stopped after the disappearance of the sugarcane industry in 1993, permanently changing the coastal environment. But, during the furrow irrigation period the flora and fauna of the estuary changed considerably (Laboy *et al*., 2006) compared to predevelopment conditions. Due to that period of high flow, in order to keep its current flora and fauna, the Jobos Bay National Estuary is demanding more and better quality of runoff water to ensure the survival of species of interest (González *et al*., 2003). Water from the Patillas-Guamaní Canals has been considered as an option to relieve the freshwater flow problems in the Jobos Bay.

The Salinas to Patillas area sustains a rapid residential growth (Figure 20) as inferred from Martinuzzi *et al*. (2007). Comparison between the population and housing data of the 1990 and 2000 Census (U.S. Census Bureau, 1990 and 2000) along with historical imagery publically available on Google Earth (Google inc., 2009), have lead to the conclusion that during the past two decades construction and population have increased at high rates, causing drastic land use changes in accordance with results found by Parés-Ramos *et al*. (2008). As in other places around the island, the post agriculture development of commercial and residential areas has imposed changes on the regional ecology (Grau *et al*., 2003). Hydrologic response of the study area has changed as a result of changes in evapotranspiration rates (Allen *et al*., 1998), infiltration and ground water recharge (Kuniansky and Rodríguez, 2010), as well as runoff volumes and velocities (O'Driscol *et al*., 2010).

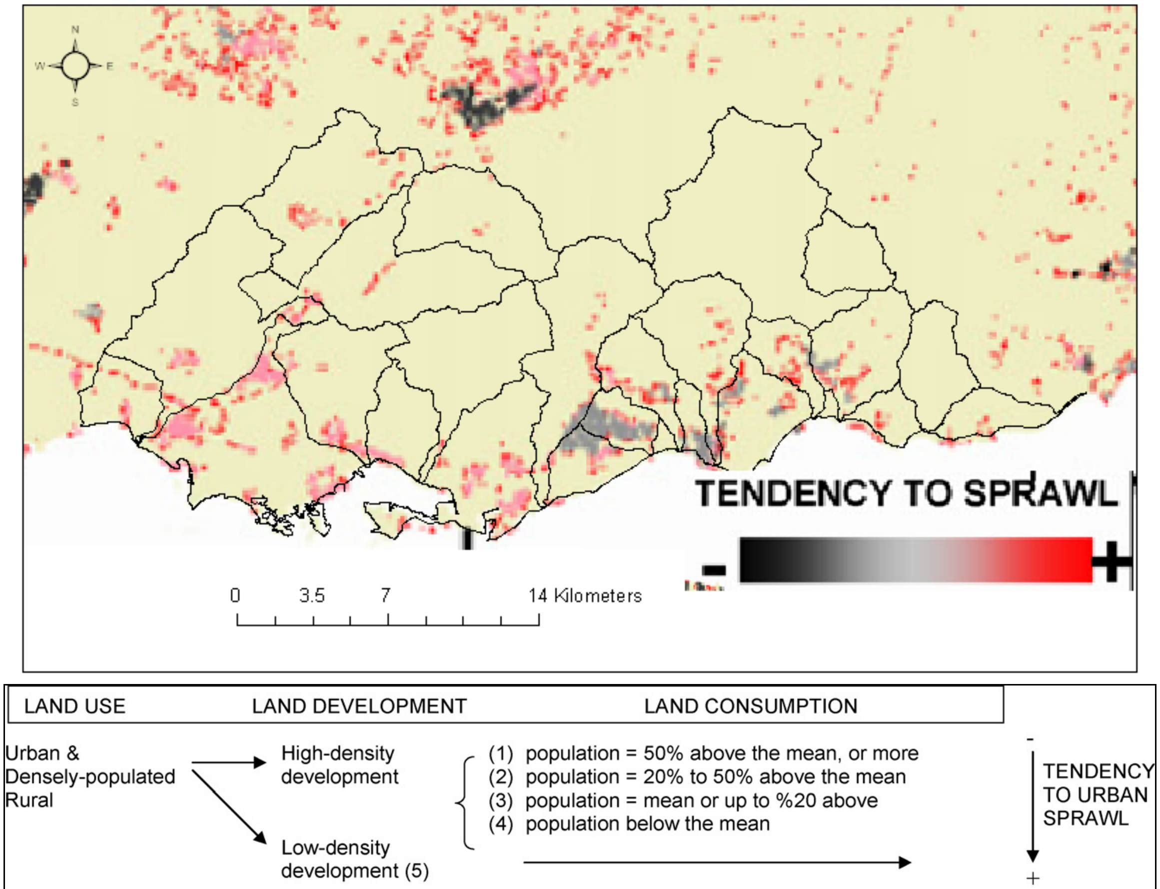

Figure 20. Developed lands showing different tendencies towards urban sprawl.[16]

16 - Martinuzzi et al. (2007)

3. Literature Review

The effects caused by changes in irrigation practices, land use and other water resources development on the groundwater recharge in the Salinas to Patillas area during the transition period from sugarcane to fallow and horticultural crops might be best described by examining changes in water dynamics. This idea follows those from McClymonds and Díaz (1972), Capiel and Calvesbert (1976), Bennett (1976), Heisel and González (1979), Quiñones-Aponte *et al.* (1997), Larsen and Concepcion (1998), Atkins *et al.*(1999), DRNA (2004), Kuniansky *et al.* (2004) and Kuniansky and Rodríguez (2010) among others, who conducted similar studies at different scales in or near the study area or in other locations of Puerto Rico with productive results.

Giusti (1971) performed one of the earliest large scale water budgets in the island. He performed a surface water budget for the Coamo quadrangle. Probably his most important finding was that, on average, 10% of rainfall in the Coamo and the Santa Isabel-Juana Díaz areas resulted in a net recharge to the aquifer. Ramos-Ginés (1994), through a second water budget, confirmed these predictions. McClymonds and Díaz (1972) performed the first estimates of infiltration from the streams to the aquifer in the western part of the Salinas to Patillas area. They estimated an infiltration rate at different times in 1962 (Table 10).

Table 10. Stream Infiltration or Seepage. [17]

Year	Infiltration rate (m^3/d)
Río Nígua de Salinas (February)	12,100
Río Seco, Quebrada Cimarrona and Quebrada Coquí (June)	9,800 to 14,800
Río Guamaní (March and October)	2,300
Groundwater discharge into Jobos Bay (August)	33,700

Through findings based on a water budget study, McClymonds and Díaz (1972) speculated that in the Salinas to Patillas area more than 10% of the rainfall may recharge the water table during wet years, less than 10% of the rainfall may recharge the water table during dry years, and that about 10% of rainfall serve as aquifer recharge during average years. Wet years was defined as years of 1,000 mm of precipitation or more, dry

17 - McClymonds and Díaz (1972)

years as years of 750 mm of precipitation or less, and average years having 750-1,000 mm of precipitation.

Capiel and Calvesbert (1976), through a surface water balance, presented a brief appraisal of the agricultural hydrology of the entire Puerto Rico almost exclusively based on climate factors. Through this publication they presented an important description of the temperature and precipitation distribution on the island. They estimated that in the south coast of Puerto Rico all the recharge occurs during the months of August and September and stated that for most of the year crops are under water deficit, meaning that irrigation is required. Capiel and Calvesbert (1976) determined that on the south coast the dry season occurs from December to April and the wet season occurs from May to November with March being the driest month and October being the wettest month in an average year. Today, this still represents one of the most important water budgets done for the entire island of Puerto Rico.

Bennett (1976) and Díaz (1976) estimated evapotranspiration from the aquifer (aquifer water loss through evapotranspiration) near the coast of the Salinas area to be between 5 and 25 cm/yr with a maximum rate of 165 cm/yr by using a regional electric analog model simulation. They utilized a groundwater budget approach as part of their model and another as part of the validation process of their results.

Heisel and González (1979) performed studies of groundwater levels and chloride concentrations in the Salinas to Patillas area. After performing a simple groundwater budget, they suggested that the use of treated waste water to recharge the aquifer was a viable solution to the decline in groundwater levels during drought conditions, but indicated that the quality of the water used could affect the quality of the groundwater of the area.

Ramos-Ginés (1994a) performed a study which assessed the effects of changes in irrigation practices on the groundwater hydrology in the Santa Isabel to Juana Díaz area. This study involved a rather simplified groundwater budget for the agricultural areas within the region. He described the hydrologic conditions of the area and presented estimates of the recharge to and discharges from the alluvial aquifer during the period of furrow irrigation prior to groundwater development that occurred before the 1930s, the period of furrow-irrigation from the 1930s through the 1980s, and the recent period of drip irrigation. He stated that; in average, about 254 mm of precipitation recharged the aquifer and about 30 percent of the irrigation water applied to fields served as groundwater recharge.

Ramos-Ginés (1994b) presented one of the most complete groundwater studies within the Salinas to Patillas region. He performed a groundwater study on the Río Majada and Río Lapa watersheds from January to December of 1989. The Río Majada and Río Lapa watersheds are located northeast of the Salinas municipality, in the south facing foothills of the Cayey mountain chain, as previously shown in Figure 6. Through a groundwater budget approach he used rainfall, pan evaporation, daily rainfall exceeding daily pan evaporation rates, base flow, river flows, river peak discharges, groundwater levels, pumping data and irrigation canal diversions to estimate groundwater recharge from precipitation, irrigation canal and irrigation practices, and from river and stream seepage. Also, he estimated average groundwater inflows and outflows to be $3.5 * 10^6$ m^3/yr and unavailable pumping data to be 12 percent of the outflows.

Quiñones-Aponte *et al.* (1997) presented a groundwater study based on a conceptual model of the aquifer system in the Salinas to Patillas area. In this study a three-layer groundwater flow digital model was constructed. Pre-irrigation/pre-development hydraulic conditions and the effects of irrigation and other aquifer development changes from 1890 to 1986 were estimated. They presented important information on groundwater flow simulation, groundwater recharge and discharge, precipitation, evapotranspiration, and seepage groundwater flow, among other relevant data and simulation outputs for their 96 year study period.

Larsen and Concepcion (1998) provided a generalized summary of the inputs, extractions, and outputs from four watersheds in and near the Luquillo mountain chain based on data gathered between 1991 and 1997. Using rainfall, runoff, public supply extraction data and estimates of groundwater losses, evapotranspiration, septic tank discharges, cloud drip, soil and aquifer properties, and other parameters they estimated the groundwater flow out of the Canóvanas, Cayaguas, Icacos and Mameyes watersheds located within the municipalities of Canóvanas, Rio Grande, Luquillo and Fajardo in the northeast area of Puerto Rico .

Kuniansky *et al.* (2004) refined previous estimates of net recharge through transient calibration of a digital groundwater flow model of the Santa Isabel quadrangle. This area is directly west of the Salinas to Patillas area of interest; which tend to receive less precipitation. They stated that aquifer recharge is 4% when there is less than 750 mm of annual rainfall for average dry years, 12% of more than 1,000 mm of the annual rainfall for average wet years, and 8% of 750-1,000 mm of annual rainfall for average years.

The Puerto Rico Department of Natural Resources (DRNA) (2004) estimated that the annual evapotranspiration is about 1,200 and 1,000 mm in the Río Grande de Patillas and Río Nigua de Salinas watersheds, respectively, where precipitation was reported to be 2,050 and 1,250 mm/year in the mentioned watersheds. Preliminary studies using Harmsen’s PR-ET (2002) computer model for a general crop indicated that actual evapotranspiration is between 1,000 and 1,500 mm/year. To validate this estimate, reference evapotranspiration was estimated using the Hargreaves-Samani method (1982) with daily data from the nearby Fortuna weather station for the calendar year 2008, where it was found that reference evapotranspiration is about 1,500 mm/year.

Kuniansky and Rodríguez (2010) presented a groundwater study on the influence of historical irrigation changes on the hydrology of the Salinas, Jobos and Aguirre area from 1986 to 2002. Kuniansky and Rodríguez aimed to “document changes in irrigation practices and aquifer development in the vicinity of the JBNEER and to quantify changes in groundwater discharge into the JBNERR area” (pp. 2). Their study area covered about

18% of the western part of the Salinas to Patillas agricultural area of interest for the current study.

Differing from the previously mentioned water balances performed in the study area and in Puerto Rico, the current study is based on physical parameters to produce estimates of evapotranspiration, applied irrigation, irrigation canal seepage, soil moisture and groundwater pumpage for irrigation on a daily basis that then are lumped in monthly and yearly estimates to produce usable results considering the process used by Brush *et al.* (2004). These components of the water balance model are crucial for agriculture, and have been taken lightly by previous researchers when studying the Salinas to Patillas hydrologic cycle as well as when studying other areas in Puerto Rico.

The proposed approach attempts to reproduce a physically oriented soil moisture water budget implemented by Young and Wallender (2003) and by Brush *et al*. (2004). Brush *et al*. (2004) in their water budget, as part of a larger investigation, estimated the groundwater recharge and groundwater pumping components of the water budget in the Grasslands drainage area of the central part of the western San Joaquin Valley, California, during the water years 1972 through 2000. Harmsen *et al*. (2010) also used similar methodology for a short period of time using satellite imagery for Puerto Rico, the Dominican Republic, Haiti and Cuba.

Brush *et al*. (2004) stated that when developing water balances, in order to quantify infiltration and ground water recharge, it is important to take into account the soil depth and plant root zone depth as well as the actual evapotranspiration. While the soil depth will determine the soil storage capacity and moisture content at all times, the root depth will determine plant water availability and the available water for deep percolation or groundwater recharge. On the other hand, the actual evapotranspiration will determine the amount of water extracted from soil reservoir. These two parameters are combined to estimate the antecedent soil moisture content that is crucial for runoff projections.

4. Materials and Methods

Following the approach taken by Brush *et al*. (2004), the crop soil moisture budget incorporates a daily soil surface processes model, a daily crop consumptive use model, and a daily crop soil moisture budget model. The soil surface processes model estimates the portion of daily precipitation that enters the soil profile. The crop consumptive use model calculates crop water demand from the daily reference/actual evapotranspiration. The crop soil moisture budget tracks the available soil moisture, applies daily infiltration and residual soil moisture to meet crop water demand, and compiles annual values of total crop water demand, crop water demand not satisfied with precipitation, and precipitation-derived recharge to the water table for each crop. These values are multiplied by crop areas for each water budget area to determine monthly and annual demand for irrigation water, which is then used as input to the water budget model.

4.1 Soil Moisture Process Model

The daily soil moisture water balance model in irrigated fields of the Salinas to Patillas area is described by the equation:

$$SM_2 = P + I - RO - ETc - Perc + SM_1 \qquad 1$$

where SM is the average soil moisture content (water depth in soil) within the determined root zone depth or soil depth, depending on weather is the soil depth or the root depths the limiting factor in the soil profile. P is precipitation, I is the effective irrigation, RO is the overland runoff, ET_c is the actual or crop evapotranspiration and Perc is the precipitation (P_{perc}) and irrigation (I_{perc}) percolation which over water table aquifers may be the same as the aquifer recharge as used in approaches by Harmsen *et al*. (2010), Shukla and Jaber (2005), Brush *et al*. (2004) Young and Wallender (2003). The subscripts 1 and 2 for the soil moisture content refer to the prior and current day, respectively. Notice that the model has daily temporal resolution, Figure 21 shows its conceptual model.

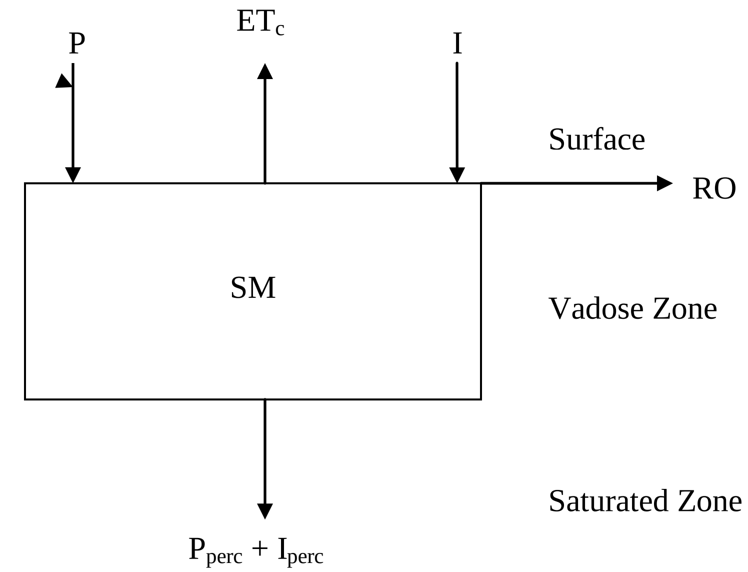

Figure 21. Conceptual model of the daily soil moisture balance for each water-budget area in the Salinas to Patillas region.

Similarly, for the non irrigated areas, the model is as follows:

$$SM_2 = P - RO - ETc - Perc + SM_1 \qquad 2$$

This model also has daily temporal resolution.

ESRI GIS software was used to delimit the boundaries of each spatial element (watersheds, basins, irrigated areas, land cover features, soils, etc) and to define the spatial resolution for each component through time depending on the available data. On the other hand, GIS is somehow a limited tool working with temporally distributed models. For the water balance temporal distribution, an Excel spreadsheet was used as an alternative to determine daily inputs and outputs. Brush *et al*. (2004) used a similar approach to address the temporal limitations of this kind of modeling.

Aware of the limited spatial resolution of the data required to perform a water balance in the Salinas to Patillas area, two different approaches were used according to the input requirements for the irrigated fields water balance (Equation 1) and the non irrigated fields water balance (Equation 2). First, instead of performing water balances for each of the 27 watersheds within the study area as originally proposed, the area was divided into two areas, separating those watersheds that receive irrigation water deliveries and groundwater pumpage for irrigation purposes from those that do not. This was done by aggregating the geographically contiguous agricultural areas under irrigation (the watersheds over the alluvial valleys along the irrigation canals) into one modeling area, and then aggregating the watersheds that do not receive irrigation water deliveries and do not have productive aquifers or non-significant groundwater yield (the mountainous areas, as shown in Figure 22 and 25) into another modeling area. The term modeling area refers to those areas where independent water balances were performed in accordance with the spatial resolution of the available data. Second, water balances were performed over conglomerate of alluvial watersheds on each of the 4 municipalities in the area (Arroyo, Guayama, Patillas and Salinas), aggregating the spatial data and considering each as independent modeling areas (Figure 22). The combination of the Arroyo, Guayama, Patillas and Salinas modeling areas results in what is called that irrigated watersheds modeling area.

Furthermore, each modeling area was subdivided into irrigated zones and non irrigated zones. Irrigated zones were identified as areas under cropland, while non irrigated zones are all other areas. This subdivision was made in order to account the groundwater recharge and extractions of direct result from irrigation water imports.

The decision to divide and subdivide the modeling areas in this way was made because irrigation water delivery data from PREPA, farmland area from the agricultural census and groundwater pumpage obtained from different publications from the USGS, which are intrinsic inputs to the water balance model, are published by municipalities. This spatial limitation, along with the lack of historical land cover maps within the study period, made it impossible to perform agricultural water balances at a watershed scale. Development of a consistent data set for crop areas, streambed seepage groundwater extractions and irrigation canal deliveries was hindered by the large assortment of data formats, significant data gaps, limited data regarding groundwater pumpage, and the different resolution and accuracy between the 1978 and 2000 land cover maps used to estimate the runoff, evapotranspiration coefficients and mean root depth.

The estimated superficial area of each modeling area is:

- Arroyo: 38,971,000 m^2
- Guayama: 133,836,000 m^2
- Patillas: 55,753,000 m^2
- Salinas: 75,191,000 m^2
- Irrigated Watersheds: 304,951,000 m^2
- Non Irrigated Watersheds: 224,783,000 m^2

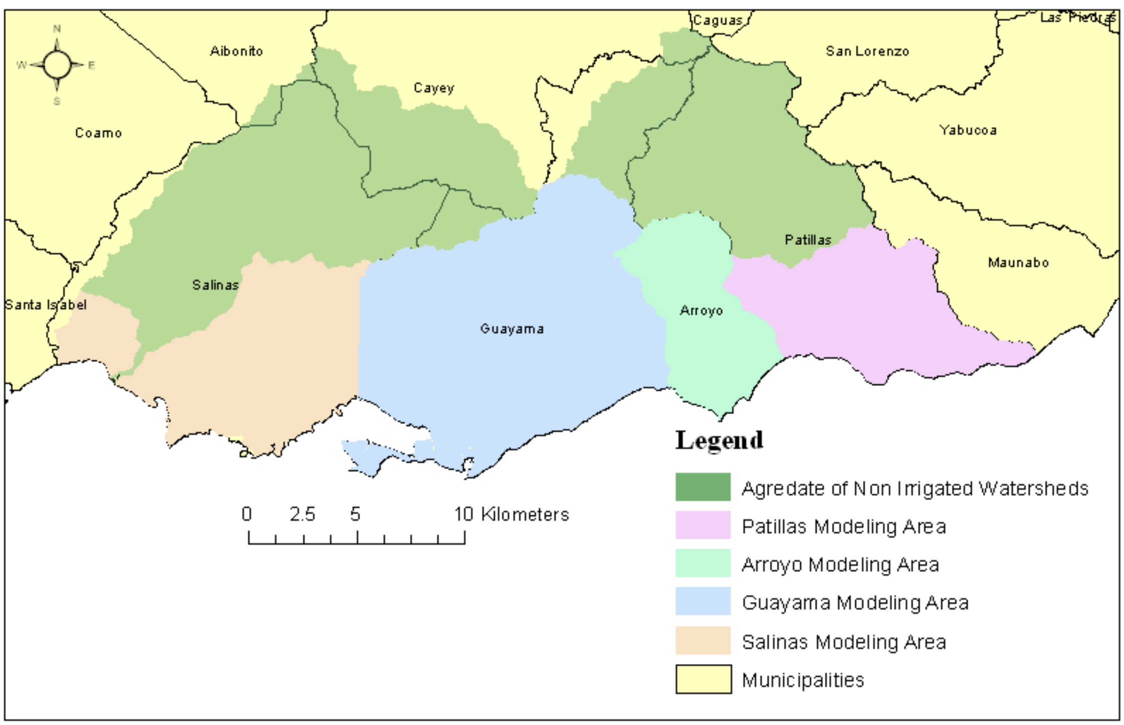

Figure 22. Division between irrigated watersheds and non irrigated watersheds.[18]

18 - Aggregation of the Patillas, Arroyo, Guayama and Salinas modeling areas represents the Irrigation Watersheds modeling area.

4.2 Conceptual Model

The created model integrates daily, monthly and annual simulation to estimate net groundwater recharge along with possible seawater interactions. In the daily process shown in Figure 21, a water budget for the vadose zone (soil moisture water budget) was created for irrigated and non irrigated areas. For irrigated areas the soil moisture budget was used to estimate the irrigation water requirement by crops and the percolation produced by each independent precipitation event (as shown in Equation 1) taking into consideration the antecedent moisture content produced by previous events and by irrigation practices. For non irrigated areas results from the soil moisture budged was used to estimate the percolation produced by each independent precipitation event (as shown in Equation 2) taking into consideration the antecedent moisture content produced by previous events.

A monthly groundwater budget or productive zone budget (Figure 23) took the lumped outputs from the daily soil moisture budget model (P_{perc} + I_{perc}) and added estimated monthly seepage from streambed (Ss), irrigation canals (Cs), and from dams (Ds) producing monthly deep percolation (Perc) which serves as input to the aquifers productive zone that in physical terms is translated as monthly groundwater recharge. Monthly outputs from the productive zone are groundwater pumpage from PRASA, PREPA, for industrial purposes, for self supply and for irrigation.

The percolation or aquifer recharge model is as follows:

$$Perc = P_{perc} + Ss + Cs + Ds + I_{perc} \qquad 3$$

where Ss, Cs and Ds are the streambed, irrigation canal and dam estimated seepage, respectively. This model has monthly temporal resolution.

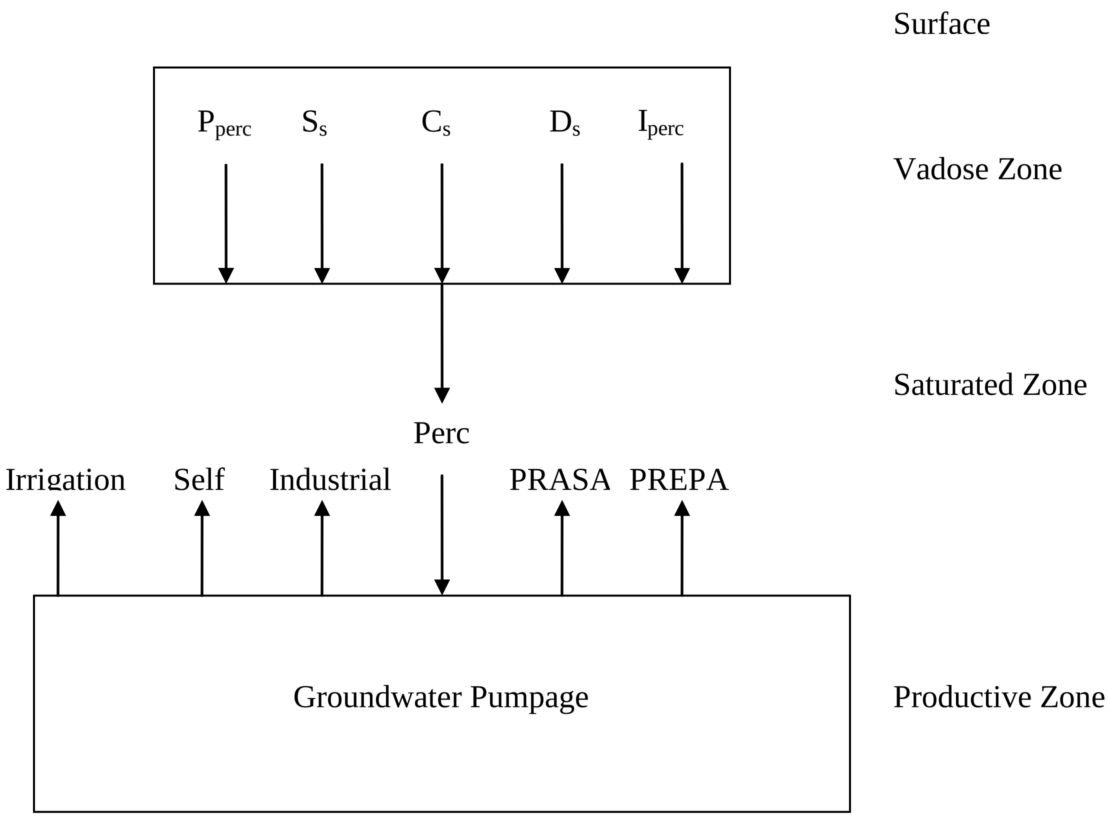

Figure 23. Conceptual model of the monthly groundwater balance for each water-budget area in the Salinas to Patillas region.

Annual groundwater budget or productive zone budget (Figure 24) used the lumped outputs from the monthly soil moisture budget model, P_{perc}, Ss, Cs, Ds and I_{perc} and added them to the estimated percolation produced by over irrigation to estimated annual deep percolation (Perc) that serves as input to the aquifers productive zone which in physical terms is translated as annual groundwater recharge. As in monthly modeling, annual outputs from the productive zone are groundwater pumpage from PRASA, PREPA, for industrial purposes, for self supply and for irrigation. Groundwater leakage to and from the ocean was speculated to occur based on annual modeling. When percolation was believed to exceed the groundwater storage capacity, groundwater leakage to the ocean was estimated to occur. Seawater leakage or saltwater intrusion was estimated to occur when the outputs from the productive zone considerably exceed its inputs.

Each factor of the model and the model itself is discussed in detail within the next several sections.

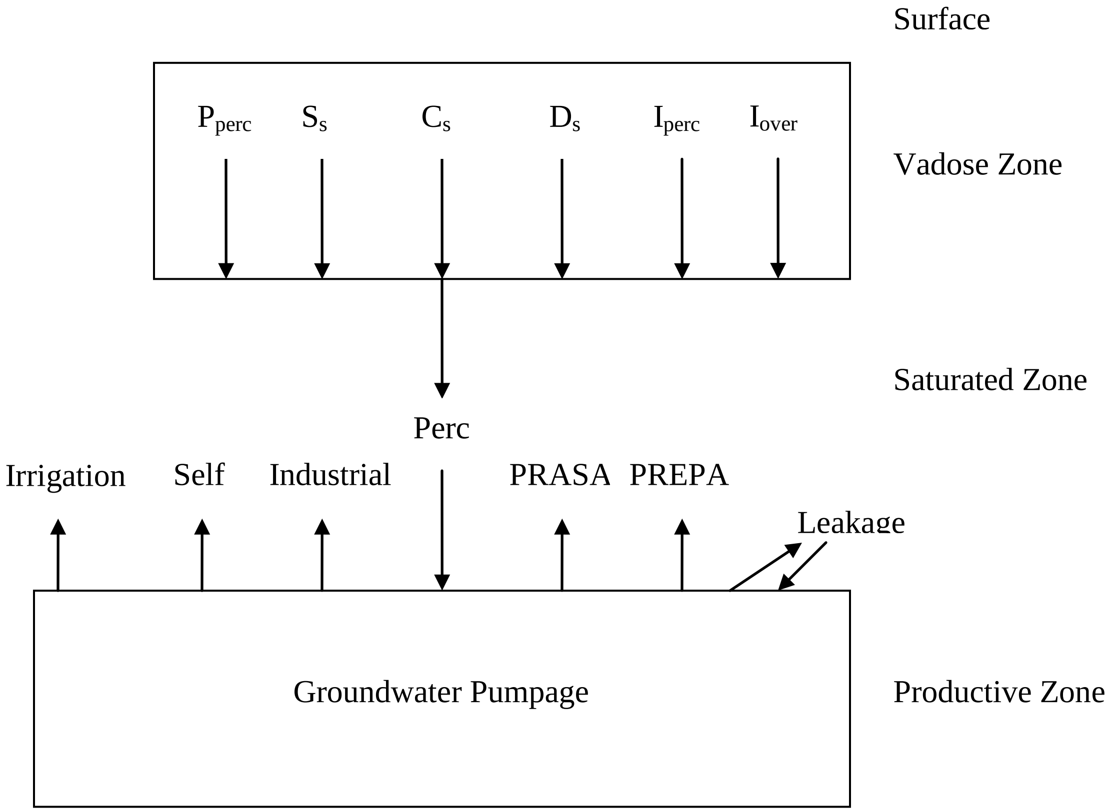

Figure 24. Conceptual model of the annual groundwater balance for each water-budget area in the Salinas to Patillas region.

4.3 Geographical Information Systems and Spreadsheets

A Geographical Information System (GIS) was created to simulate the spatial distribution of the model using ArcGIS (ESRI, 2009). Layers of agricultural land, irrigated land, main crops, land use, land cover, canopy, soil type and characteristics, watershed, sub-watersheds, rivers and streams, reservoirs and lagoons, aquifer characteristics, local geology, Patillas-Guamaní irrigation canals, impervious areas, surface and ground water extractions, weather station locations, topography and modeling areas were created and/or obtained from diverse sources (Table 11). Temporal parameters like precipitation, present and antecedent soil moisture content, runoff, irrigation depth and irrigation scheduling, potential and actual evapotranspiration, etc., were established for each modeling area using spreadsheets.

Table 11. GIS layers, and its sources, to be used for the study.

Layer	**Source**
1978 Land Cover	Olga M. Ramos González, USDA Forest Service International Institute of Tropical Forestry (IITF)
2000 Land use	USGS National Land Cover Database Zone Commonwealth of Puerto Rico (2001) found in Kennaway and Helmer (2007) through Alejandra Rojas-González, UPRM Doctorate Student
2000 Land cover	USGS National Land Cover Database Zone Commonwealth of Puerto Rico (2001) found in Kennaway and Helmer (2007) through Alejandra Rojas-González, UPRM Doctorate Student
2000 Land canopy	USGS National Land Cover Database Zone Commonwealth of Puerto Rico (2001) found in Kennaway and Helmer (2007) through Alejandra Rojas-González, UPRM Doctorate Student
Soil type and characteristics	USDA-NRCS Web Soil Survey and USDA-NRCS Soil Data Mart
Watersheds	PR Planning Board, GIS Division, GeoDATA files through Oscar Martinez, UPRM Doctorate Student
Rivers and streams	PR Planning Board, GIS Division, GeoDATA files through Oscar Martinez, UPRM Doctorate Student
Aquifers characteristics	PR Planning Board, GIS Division, GeoDATA files through Oscar Martinez, UPRM Doctorate Student
Patillas-Guamaní irrigation canals	Irizarry (2010)
2000 Impervious area	USGS National Land Cover Database Zone Commonwealth of Puerto Rico (2001) found in Kennaway and Helmer (2007) through Alejandra Rojas-González, UPRM Doctorate Student
Surface and ground water extractions	PR Planning Board, GIS Division, GeoDATA files through Oscar Martinez, UPRM Doctorate Student
Weather station locations	CLIMOD weather station metadata

4.4 Precipitation

Precipitation (P) was used as a uniform input for each modeling area of the water balance. Several weather stations are or were located within and near the study area. These weather stations are presented in Table 12, and independent of the period of record, each of them counts with useful data to estimate different factors like evapotranspiration, and to get an idea of the areal distribution of precipitation to estimate missing data. Climate data from these stations was obtained through the Climate Information for Management and Operational Decisions (CLIMOD) system thanks to the cooperation of Dr. Amos Winter (Professor of paleoceanography and climatology from the Department of Marine Sciences of the University of Puerto Rico at Mayagüez Campus, Personal Comm., October 2010) and his graduate students.

Table 12. Weather stations located within or near the study area. [19]

Station Name	Station Code	Available Data*	Data Period	Elevation (m)
Carite Dam	661701	PRCP, Tmax, Tmin, Tobs	1955/01 to 1980/04	551
Carite Plant	661712	PRCP	1955/01 to 1980/03	295
Guayama	664193	PRCP, Tmax, Tmin, Tobs	1911/01 to 2010/12	22
Patillas Dam	666904	PRCP, Tmax, Tmin, Tobs	1931/01 to 1969/01	73
Patillas	666900	PRCP	1982/04 to 2010/12	14
Santa Isabel	668940	PRCP	1955/01 to 2010/12	9
Maunabo	666050	PRCP	1899/05 to 2010/12	15
Coamo	662723	PRCP	1955/01 to 2010/12	111
Aibonito	660158	PRCP, Tmax, Tmin, Tobs	1906/01 to 2010/12	710
Aguirre	660152	Evap, PRCP, Tmax, Tmin, Tobs WDMV	1955/04 to 2010/12	8
Aguirre	660147	PRCP, Tmax, Tmin,	1931/01 to 1966/10	7.6
Jájome Alto	664867	PRCP	1970/1 to 2010/12	720
Josefa	66497	PRCP	1955/1 to 1968/12	9
Guavate Camp	664115	PRCP	1969/1 to 1994/12	780
Sabater	668623	PRCP	1955/1 to 1969/1	21
Melanía Dam	666128	PRCP	1955/1 to 1969/1	42
Yaurel	669884	PRCP	1955/1 to 1969/3	39

PRCP = Daily Precipitation, TMAX = Maximum Temperature, TMIN = Minimum Temperature, TOBS =Temperature at Observation Time, WDMV =24-Hour Wind Movement, EVAP =Pan Evaporation.

Originally, areal distribution of precipitation for selected events was estimated using an ESRI GIS based Isohyetal and Thiesen Methods. This method seemed to work fine for the weather stations in the lower areas, but didn't quite work in the mountainous areas, probably because rain gauges are commonly located at lower elevations in the mountainous regions and/or on watersheds with different precipitation tendencies, causing consistent underestimation of mean areal precipitation (NWS, 2002). Alternatively, precipitation depth from the nearest station with precipitation data for the given day was used as the precipitation for the station with the missing data as presented by Brush *et al*. (2004).

For each day from January 1, 1980, through December 31, 2010, a single daily precipitation value and a single daily maximum temperature, minimum temperature and reference evapotranspiration (ET_0) value was assumed to apply uniformly to each modeling area (Young and Wallender, 2003, Brush *et al*., 2004). No single station had a complete record of precipitation or air temperature measurements for the entire study period and most of them had prolonged periods of missing data. For each day of missing

19 - *Parameters collected at weather stations

weather data, the recorded parameter from the nearest station was used as a single daily value (Brush *et al*., 2004). If the daily value for precipitation, maximum temperature and/or minimum temperature was also missing for the 3 nearest weather stations, then the value for that day was obtained from weather generated data using ClimGen weather generator (Campbell, 1990) for the original station. ClimGen is a stochastic model that generates daily maximum and minimum temperature, and precipitation depth based on 10 to 30 years of historical daily weather data. In this case weather data was generated for the study period for determined weather station within each modeling area (Table 13) with the intention of using it to fill missing data from the weather station itself.

Table 13. Modeling areas.[20]

Modeling Area	**Weather Station**	**Missing Data Station**	**Validation Station**
Patillas	Patillas	Guayama, Aguirre	Patillas
Arroyo	Guayama	Patillas, Aguirre, Santa Isabel	Yaurel
Guayama	Guayama	Patillas, Aguirre Santa Isabel	Melanía
Non Irrigated watersheds	Jájome Alto	Aibonito, Guayama	Carite
Salinas	Aguirre	Guayama, Santa Isabel	Sabater

The reliability of the precipitation data obtained from CLIMOD and the method for estimating missing precipitation data was assessed by comparing a year worth of daily precipitation data lumped into monthly resolution with monthly data for the same year obtained from independent weather stations operated by the Guayama Irrigation District of PREPA. The Guayama Irrigation District of PREPA operated several weather stations within the study area between January of 1991 and June of 1998, where data from the early years is considered to be more accurate and taken with more consistency than the latter years. Table 13 and Figure 25 present the modeling areas and the locations of the weather stations used for modeling and assessment purposes. Table 13 presents the combination of weather stations and modeling areas with its first column showing the modeling area, the second column presenting the weather station to be used for modeling in that area, the third column representing the weather stations to be used to fill in missing daily data and the fourth column representing the weather station used for assessment of the precipitation data and missing data estimation method.

20 - Weather stations to be used in the modeling area, and weather station used to validate missing weather data approach.

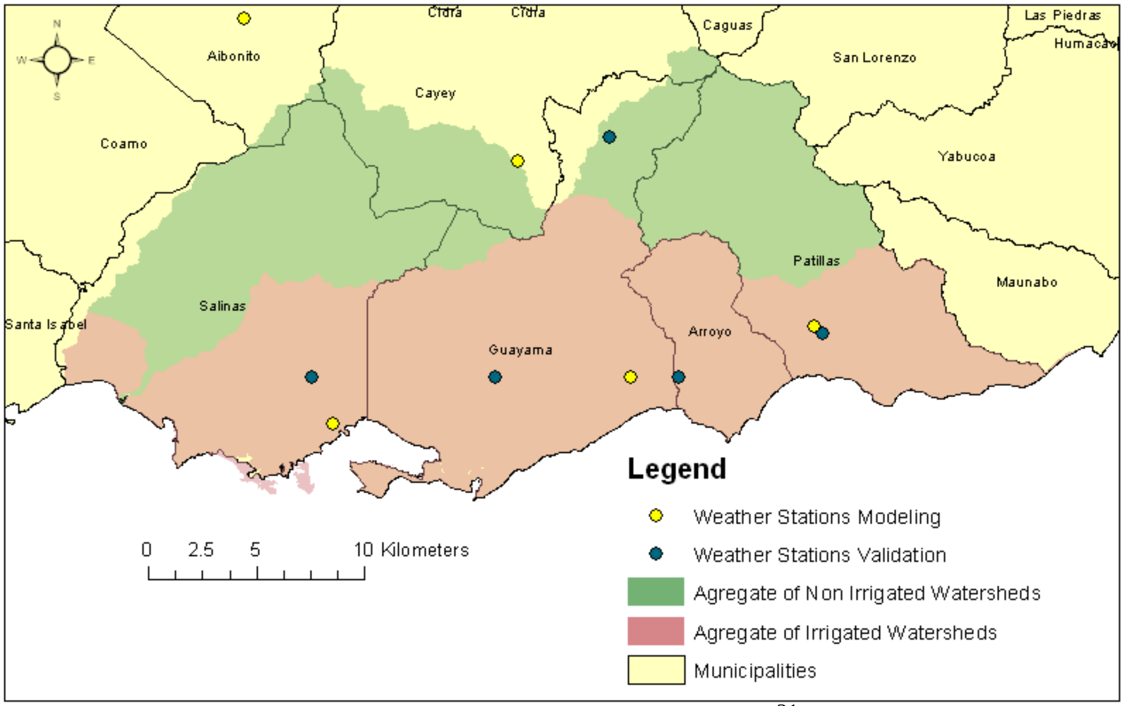

Figure 25. Weather stations used for water balance modeling.[21]

Even when the monthly precipitation data obtained from the Irrigation District lacks information about the regularity and consistency of measurement where it is believed that measurements after the first few years were not taken in a regular and standard basis, this is the only independent data set of climate data found within the study area. Plot of both monthly precipitation data sets (Figures 26 through 30) show an excellent fit of the data where all trend lines count with slopes close to one, intercept bellow 20 mm and correlation over 0.80 which is a good fit between the precipitation data used for modeling purposes in the *y* axis and the obtained from the Irrigation District in the *x* axis. Although trend line analysis show that precipitation data used for modeling purposes tend to be greater than the data used for assessment, this is only significant for the Guayama/Arroyo modeling area where 66 days or 18% of the precipitation data for the Guayama weather station was missing during the year 1991, data that was substituted with data from the nearby stations or ClimGen generated data.

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21 - Estimate of missing data assessment. From east to west, location of the weather stations for modeling purposes (yellow dots): Patillas, Guayama, Jájome Alto, Aguirre, Aibonito, Santa Isabel. In the same way, the approximate locations of the stations with data used for assessment purposes (blue dots) are: Patillas, Yaurel, Carite, Melanía and Sabater.

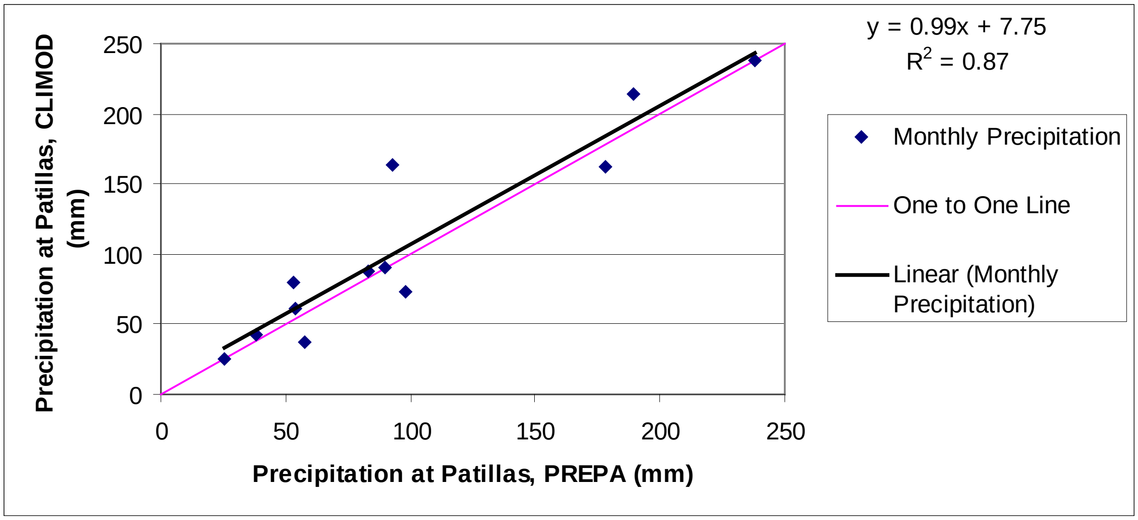

Figure 26. Precipitation data relationship for the Patillas modeling area.[22]

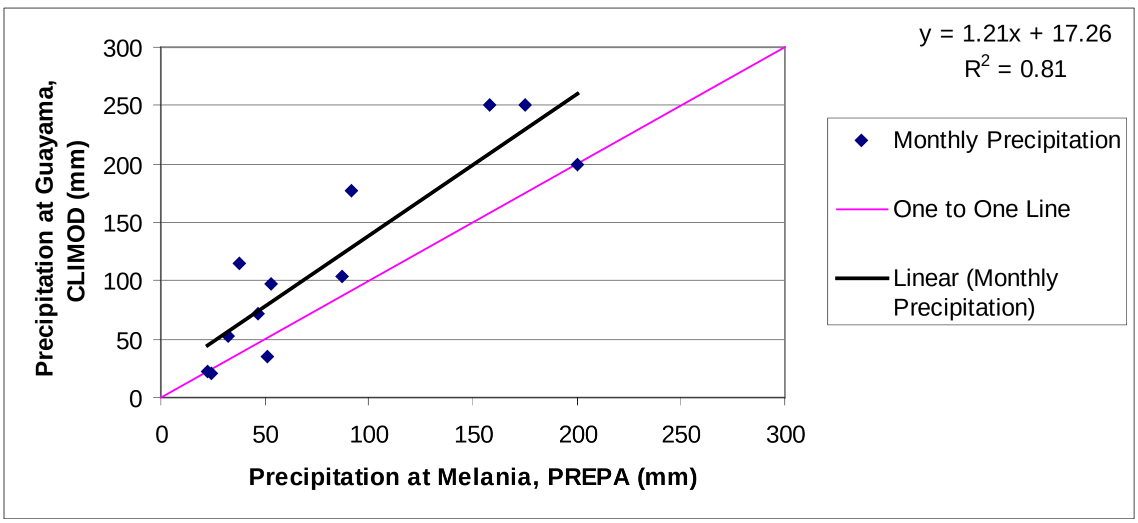

Figure 27. Precipitation data relationship for the Guayama modeling area.[23]

22 - Year 1991, where precipitation data obtained from the Patillas weather station of PREPA (Guayama Irrigation District, 2010) was compared to precipitation data obtained from the Patillas weather station of CLIMOD. Precipitation data for modeling purposes counts with 0 days of missing data for this year.

23 - Year 1991, where precipitation data obtained from the Melanía weather station of PREPA (Guayama Irrigation District, 2010) was compared to precipitation data obtained from the Guayama weather station of CLIMOD. Precipitation data for modeling purposes counts with 66 days of missing data for this year.

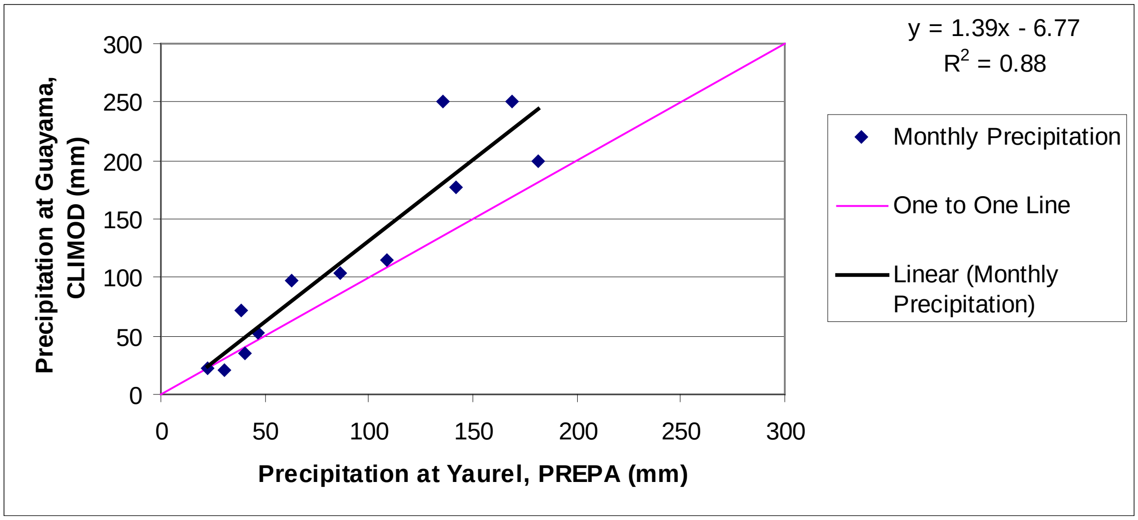

Figure 28. Precipitation data relationship for the Arroyo modeling area.[24]

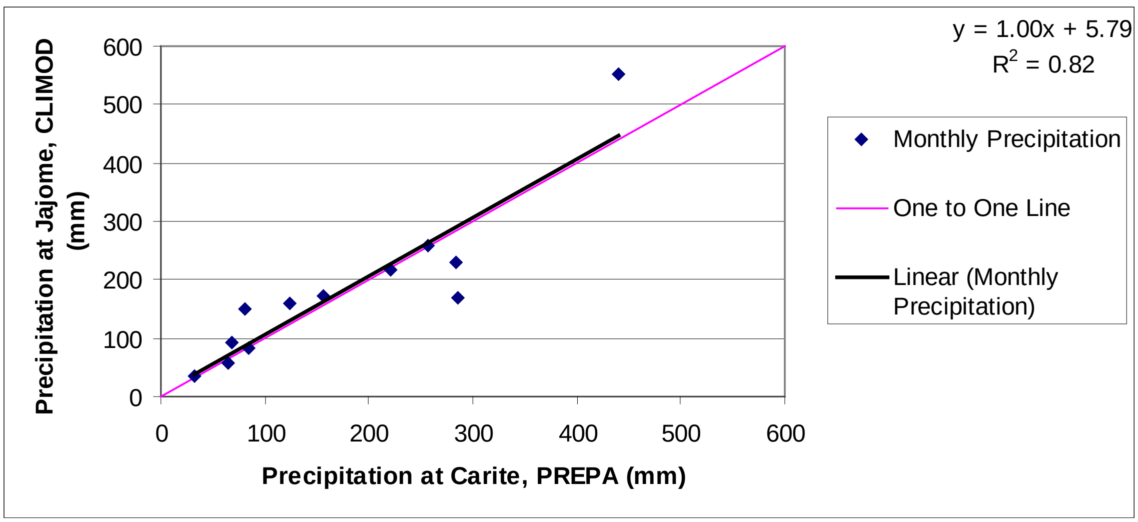

Figure 29. Precipitation data relationship for the Non Irrigated Watersheds modeling area.[25]

24 - Year 1991, where precipitation data obtained from the Yaurel weather station of PREPA (Guayama Irrigation District, 2010) was compared to precipitation data obtained from the Guayama weather station of CLIMOD. Precipitation data for modeling purposes counts with 66 days of missing data for this year.

25 - Year 1992, where precipitation data obtained from the Carite weather station of PREPA (Guayama Irrigation District, 2010) was compared to precipitation data obtained from the Jájome Alto weather station of CLIMOD. Precipitation data for modeling purposes counts with 5 days of missing data for this year.

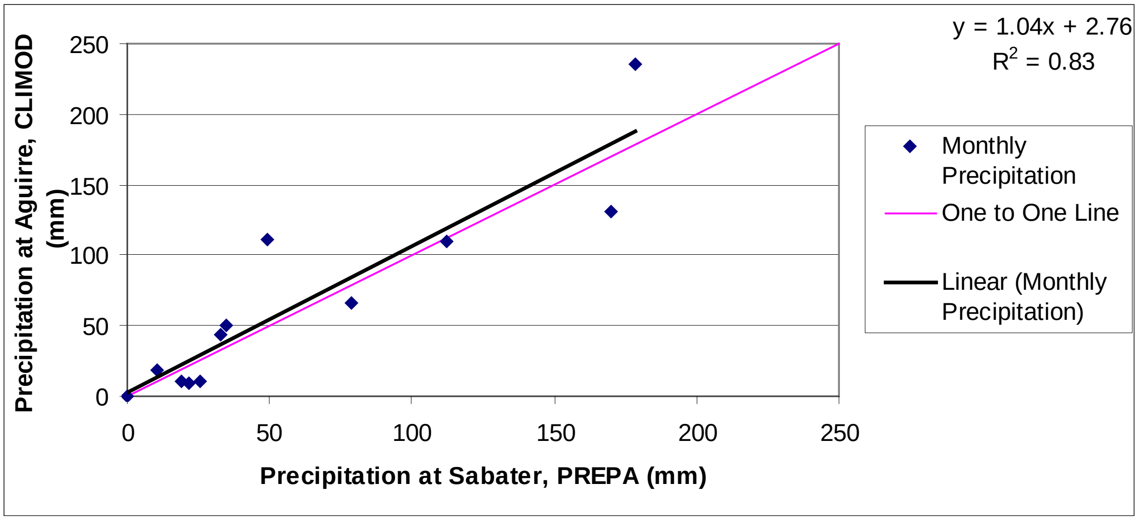

Figure 30. Precipitation data relationship for the Salinas modeling area.[26]

4.6 Irrigation Efficiency

Irrigation efficiency can be defined in terms of the irrigation system performance, uniformity of the water application, and the response of the crop to irrigation (Howell, 2003). Apart from irrigation water that is deliberately applied over the crop needs, irrigation water may cause or stimulate seepage past the root zone (deep percolation) from all three of the above efficiency factors.

A low irrigation system performance can cause seepage when the losses in the process of delivering irrigation water to the fields are high, as is the case of many flood and furrow irrigation systems. Groundwater recharge through irrigation water seepage may also occur because of the inability of the irrigation systems to reach uniformity of water application in an efficient way, where sometimes irrigation managers have to over irrigate some parts of a field in order to reach the required irrigation depths. The significance for groundwater recharge due to over irrigation in order to reach uniformity depends on the irrigation system and the irrigation manager. For example, to reach uniformity in the application of the required irrigation depth, flood and furrow irrigation

26 - Year 1991, where precipitation data obtained form the Sabater weather station of PREPA (Guayama Irrigation District, 2010) was compared to precipitation data obtained from the Aguirre weather station of CLIMOD. Precipitation data for modeling purposes counts with 1 day of missing data for this year.

tends to over irrigate a lot more than sprinkler irrigation which at the same time tends to over irrigate a lot more than drip and micro systems.

In the other hand, the response of the crop to irrigation stimulates groundwater recharge instead of directly causing it as the previous two factors. Crops with a low allowable depletion of soil moisture; as most horticultural crops are, requires similar amount of irrigation water than crops with higher allowable soil moisture depletion but in more frequent applications. This is to keep the soil moisture high enough for the crop to reach its maximum yield. By keeping high soil moisture, there is a higher probability that plant available water provided by irrigation in the soil will turn to be gravitational water if soil reaches saturation. This may happen if over irrigation occurs or if there is a precipitation event shortly after irrigation has taken place.

In the Salinas to Patillas area, furrow irrigation is the system with higher potential of over application of irrigation water to the crops having as consequence the production of deep percolation and eventual groundwater recharge. Irrigation from drip and sprinkler irrigation systems typically does not provide significant water for deep percolation, although it stimulates percolation when it rains in subsequent days after irrigation has taken place depending on the soil water content after the irrigation event. Center pivots are not representative in Puerto Rico but there are at least three pivoted irrigation systems in the study area with intakes directly in the south coast aquifer. Pivoted irrigation systems may or may not contribute to deep percolation depending on their management and efficiency.

A 31 year continuous daily irrigation scheduling; which procedure is discussed later on, was developed to estimate the net irrigation requirements for two periods, January 1, 1980 to December 31, 1993 when sugarcane production was present, and the period from January 1, 1994 to December 31, 2010 when horticultural crops were dominant. Input parameters for the first period were estimated based on the 1978 Land Cover for Puerto Rico (Ramos and Lugo, 1994) and the parameters for the second period were estimated from the 2000 Land Cover for Puerto Rico (Kennaway and Helmer, 2007). Where net irrigation requirement is the irrigation needed by crops to satisfy evapotranspiration rate, or in other words, the net irrigation requirement is the crops irrigation requirement minus all possible losses, while irrigation water requirement is the irrigation water required to satisfy the irrigation depth under real world conditions.

Single irrigation efficiency values were assumed for each modeling area based on the weight average efficiency for the conglomerate of irrigation systems presents for five different irrigation periods. The irrigation periods and the irrigation system distribution within each period was estimated based on data from the different agricultural census for Puerto Rico shown in Table 6 based on the assumptions presented in Table 14. Furrow irrigation efficiency was assumed to be 65%, sprinkler irrigation 75% and drip irrigation 90%, as given by James (1988) while 80% efficiency was assumed for irrigation systems referred as “others” by the agricultural census. Other irrigation systems may include flood irrigation, underground micro irrigation, water table management, micro sprinklers, center pivots, and big guns, among others.

Table 14. Irrigation periods for modeling purposes.

Period	**Description**
1980 -86	Period with the highest sugarcane production, lowest irrigation efficiency
1987-93	Period if transition from sugarcane to horticultural production
1994-99	Period of increasing horticultural production
2000-04	Period of highest irrigation efficiency
2005- 10	Period of slight drop in irrigation efficiency

Irrigation water requirement was assumed to equal the irrigation depth requirement estimated from an irrigation scheduling model over the estimated irrigation efficiency. Although the factors that affect the irrigation efficiency are expected to vary in time reflecting improvements in irrigation application technologies, changes in crops, irrigation tendencies and water availability, owing to a lack of data regarding short term changes in irrigation practices a single time invariant efficiency was used for each water budget area for each irrigation period. Table 15 presents each modeling area with its weighed irrigation efficiency for the different irrigation periods. In the particular case of the Arroyo modeling area, the 2007 USDA Agricultural Census show that there were no irrigation systems active when the survey was made, but irrigation water delivery data from PREPA show that irrigation did took place during that year.

Table 15. Irrigation Efficiency for each modeling area during different periods.

Year	Arroyo	Guayama	Patillas	Salinas	Global
1980-86	65	65	65	67	65
1987-93	65	73	67	74	71
1994-99	65	81	68	81	76
2000-04	65	88	82	87	85
2005-10	65	82	78	85	83

For the same reasons that a single irrigation efficiency value was used, a single fraction of the irrigation water requirement was assumed to percolate past the root zone to recharge the aquifer based on the weight average irrigation efficiency (Table 16) of each modeling area where 20% of flood irrigation requirement and 5% of sprinkler and center pivot irrigation water requirement was assumed to percolate past the root zone to the groundwater while none of the irrigation water requirement from drip irrigation areas does. Also all imported water above the irrigation requirements was assumed to recharge the aquifer as a direct result from over irrigation.

Table 16. Percentage of irrigation water requirement assumed to recharge the aquifer through percolation past de root zone.

Year	Arroyo	Guayama	Patillas	Salinas	Total Area
1980-86	20.0	20.0	20.0	18.0	19.0
1987-93	20.0	13.2	17.5	12.3	14.8
1994-99	20.0	6.4	15.0	6.5	10.5
2000-04	20.0	1.3	3.9	1.4	3.3
2005-10	20.0	5.0	10.0	3.6	4.9

In a recent investigation, Arnold (2011) reported that deep percolation estimates from a sprinkler-irrigated site in the Weld County of Colorado during the years 2008 and 2009 to range from 5 to 14 percent of irrigation water applied during the research period. Based on results from Giusti (1971) and Bennett (1976) found in Quiñones-Aponte *et al.*, (1997) and Kuniansky and Rodríguez (2010), in the Puerto Rico South Coast about 30 percent of the water applied as furrow irrigation returned to the aquifer by percolation processes. Kuniansky *et al.* (2004) estimated that as much as 30 percent of applied irrigation water to sugarcane crops contributed to groundwater recharge in the Santa

Isabel area and none of the drip irrigation water does. Kuniansky and Rodríguez (2010) assumed that groundwater recharge from irrigation in the Salinas area ceased after 1993 with the cease in sugarcane production. Although it is widely known that the contribution of drip irrigation to groundwater recharge is negligible, groundwater recharge in the Salinas area could not have ceased after the sugarcane production if we take into consideration that there still in use other irrigation systems in the area such as sprinkler, center pivots and furrows as reported by the 1998, 2002 and 2007 USDA Agricultural Census and that contribution to groundwater recharge also comes from irrigation water conveyance and storage.

4.7 Irrigation Water Deliveries by Guayama Irrigation District of PREPA

Monthly deliveries of surface water for irrigation purposes (water sold plus concessions) was obtained from the Guayama Irrigation District (2010) of PREPA. Monthly deliveries of irritation water by PREPA do not necessarily represent the actual water applied to crops within the month since many farmers import water from the irrigation canals to their in farm storage facilities (typically irrigation ponds) so it's readily available to be used when needed. Nonetheless, the water imported to the in farm storage facilities that is not evaporated, eventually reach the field as irrigation.

The surface water delivery data was divided into two groups based on its completeness. First, the data set with more information is the one for the irrigated watersheds modeling area (Figure 31) which cover all the watersheds influenced by the Patillas-Guamaní irrigation canals. This data set is based on a combination of monthly water deliveries from PREPA along with annual deliveries data published by Quiñones-Aponte *et al.*, (1997). The second set of data is composed of surface water deliveries for the rest of the modeling areas which are the Salinas, Guayama, Arroyo and Patillas. The data set counts with prolonged gaps of missing information that were filled with estimates based on linear regression analysis.

Monthly irrigation water deliveries for the irrigated watersheds modeling area is consistent for most years, having 9 years of missing and/or incomplete data within the 31 year study period. This years are 1980, 81, 82, 83, 86, 87, 88, 89 and 90. Fortunately annual irrigation water deliveries for these years have been published by Quiñones-Aponte et al., (1997), from which reconstruction of the monthly water deliveries for the irrigated watersheds modeling area was based on. The inputs for this reconstruction were estimated as a direct proportion between annual net irrigation requirements estimated from an irrigation scheduling model (Figure 31) and water deliveries data for the irrigation period extrapolated to monthly net irrigation requirements.

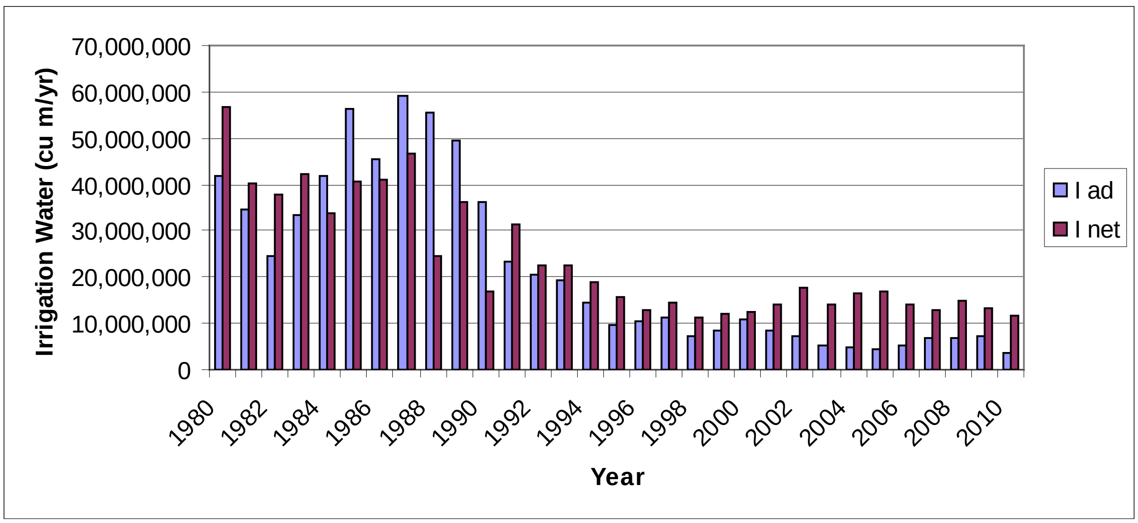

Figure 31. Total irrigation water deliveries. [27]

Figure 31 shows the correlation between surface water deliveries and irrigation water net requirements when compared in a yearly basis. The worst correlation exists for the period from 1985 to 1990 (Figure 31 and 32) when irrigation water delivered was more than double the required. This can be attributed to 2 possible factors:

1. there might have been more irrigated land than what was reported by the 1992 USDA Agricultural Census and by Molina-Rivera and Dopazo (1995) and Dopazo and Molina-Rivera (1995) used to estimate the

27 - Deliveries by the Patillas-Guamaní canals (I ad) and estimated net irrigation requirement (I net). (Guayama Irrigation District, 2010).

monthly water requirement volume which may have resulted in an under estimation of the actual irrigation water requirement,

2. for some reason there might have been a considerable reduction in groundwater pumpage that caused an increase in demand of surface water for irrigation purposes.

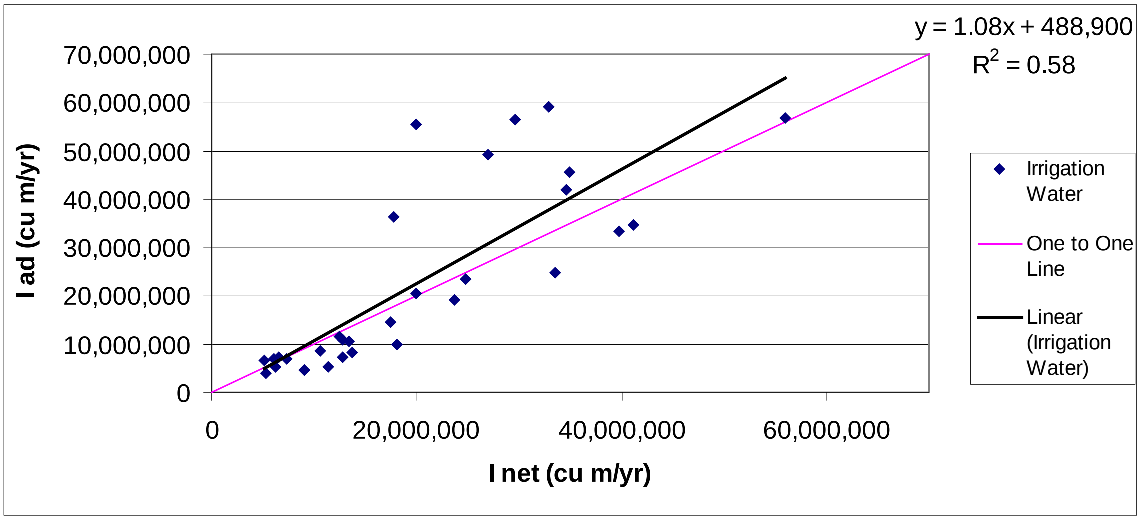

Figure 32. Net irrigation requirement (I net) vs surface water deliveries by PREPA (I ad), a yearly basis comparison.

Surface water deliveries to farms for the Salinas, Guayama, Arroyo and Patillas modeling areas count with 10 years of partial and/or full data; this is a considerable reduction in the actual data from the total monthly deliveries used for the irrigated watersheds modeling area. The years with data are 1980, 84, 85, 90, 91, 92, 93, 2006, 07 and 08, which are representative of three of the five irrigation periods established for modeling purposes. For the Salinas, Guayama, Arroyo and Patillas modeling areas, yearly water deliveries were used to estimate the amount of surface water delivered to farms within the three decades represented. This was done by assuming that there is the same linear relationship between net irrigation requirement and irrigation water deliveries between years with data and years without data.

This approach was assessed by comparing the sum of the estimated yearly irrigation water deliveries for the Salinas, Guayama, Arroyo and Patillas modeling areas with the irrigation water deliveries obtained from PREPA resulting in an excellent fit as shown in Figure 33. This is a regression analysis of the conglomerate for the entire study period of the lumped annual irrigation water deliveries for the Salinas, Guayama, Arroyo and Patillas modeling areas (I adm) compared to the total irrigation water deliveries from PREPA (I ad).

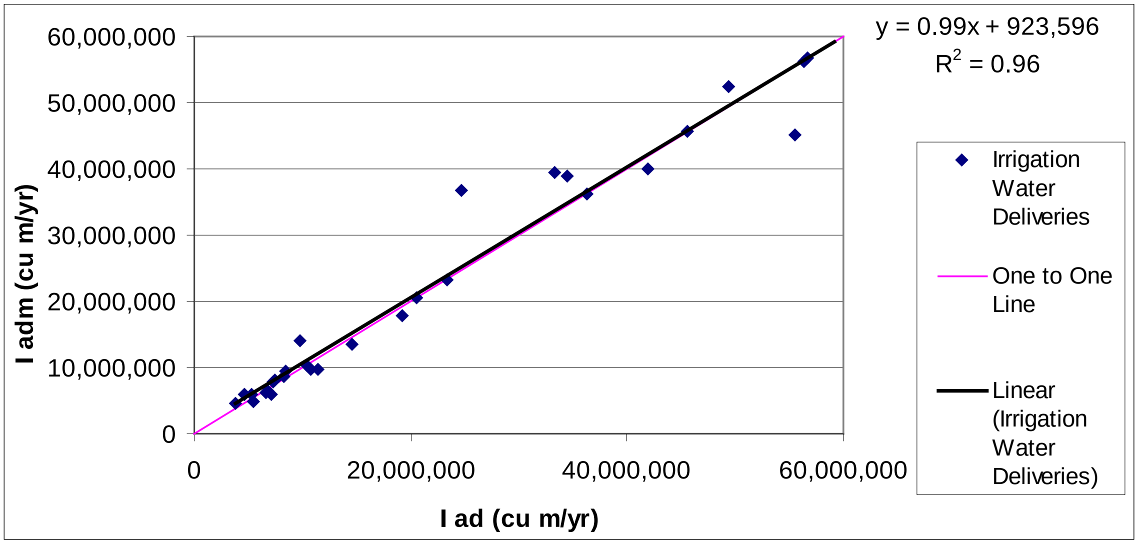

Figure 33. Yearly product from estimated monthly irrigation water deliveries (I adm) from 1981 through 1989 compared to those published by Quiñones-Aponte et al., (1997) referred as I ad.

Once the yearly irrigation water deliveries was estimated for the Salinas, Patillas, Arroyo and Guayama modeling areas, the monthly irrigation water deliveries was estimated as a direct proportion between annual net irrigation requirements estimated from an irrigation scheduling model and the water deliveries estimated for the irrigation period extrapolated to monthly irrigation requirements. Actual and estimated annual irrigation water deliveries for the Salinas, Guayama, Arroyo and Patillas modeling areas are shown in Figure 34. For validation of this process refer to Appendix III.

Even though monthly surface water deliveries data for both modeling approaches counts with prolonged period of missing information that was filled with a simple linear regression approach, the data still represents an extremely valuable asset for the estimation of aquifer recharge.

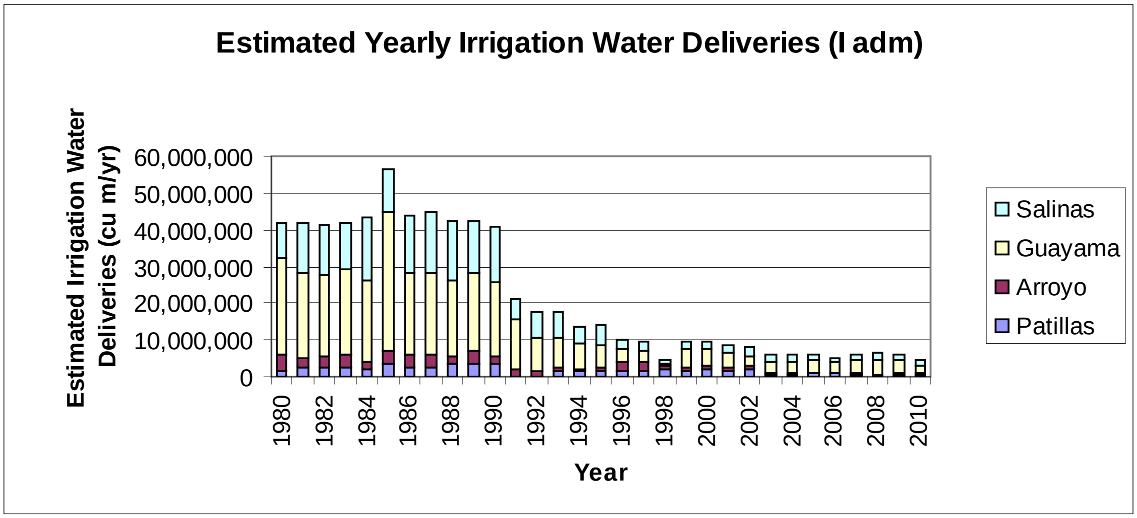

Figure 34. Reconstruction of yearly irrigation water deliveries for each modeling area.

4.8 Groundwater Extractions for Irrigation Purposes

Groundwater pumpage requirement (Pw. req) for irrigation purposes in the Salinas, Guayama, Arroyo and Patillas modeling areas as well as for the irrigated watersheds modeling area was assumed to be equal to the net irrigation water requirements (I net) obtained from an irrigation scheduling considering the weighted average irrigation system efficiency ($I_{eff.}$) for the different modeling periods presented in Table 15 minus the surface water imports presented in the last section (I ad or I adm). Equation 4 is the mathematical representation of the groundwater extraction for irrigation purposes for each modeling area which can be applied to any temporal resolution:

$$Pw.\ req = (I\ net/I_{eff.}) - (I\ ad\ or\ I\ adm) \quad (4)$$

Results from the irrigation scheduling approach to estimate groundwater pumpage for the Salinas area was compared to those published by Kuniansky and Rodríguez (2010). Their study area is bigger than the Salinas modeling area, which includes the Río Jueyes located west of Salinas through Río Guamaní which is east of Salinas where we have by far, the biggest concentration of agricultural wells is within the Salinas modeling area. Figure 35 present a comparison between estimates of yearly groundwater pumping from agricultural wells in the vicinity of Salinas. Kuniansky and Rodríguez (2010) groundwater pumpage for agricultural purposes is based on field surveys performed in 1986 and 2002, along with irrigation requirement estimates based on crop and acreage estimated from aerial photos and satellite imagery (José Rodríguez, USGS hydrologist and author of Kuniansky and Rodríguez (2010), personal comm., November 2011).

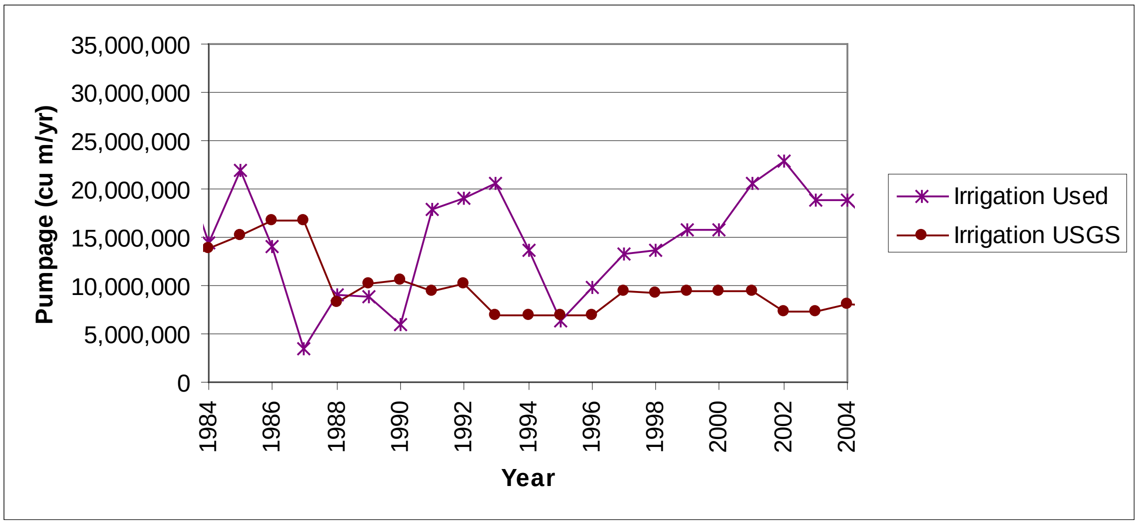

Figure 35. Comparison of yearly estimates of groundwater pumpage for irrigation water in the Salinas area based on an irrigation scheduling model (Pw. req) and published by Kuniansky and Rodríguez (2010) referred as USGS.

The marked difference in groundwater pumpage for irrigation purposes between estimates is due to the assumed irrigation application rate, along with differences in irrigated area estimates and irrigation period. In terms of irrigation water application, Kuniansky and Rodríguez (2010) assumed a crop water application rates of 1220 mm/yr for sugarcane, 610 mm/yr for row crops (horticultural crops), and 305 mm/yr for pastures. Here the irrigation application was based on net crop-water requirements, irrigation efficiency and crop irrigation coefficients. This resulted in a crop water application rate between 1075 mm/yr as a minimum and 1650 mm/yr as maximum for the 31 year study period in the Salinas area which is much higher than the one used by Kuniansky and Rodríguez (2010). In terms of irrigated area estimates, Kuniansky and Rodríguez (2010), irrigated area estimates came from aerial photos and satellite imagery (José Rodríguez, personal comm., November 2011). For the current study, area estimates are based on reports by the USDA Agricultural Census and from the Estimated Water Use in Puerto Rico Reports done by Torres-Sierra and Avilés (1986), Molina-Rivera and

Dopazo (1995), Dopazo and Molina-Rivera (1995) and Molina-Rivera (1998). Similarly, Kuniansky and Rodríguez (2010) used typical planting dates and life cycles for different crops to estimate the irrigation temporal distribution, while in the current study the irrigation was assumed to be uniform year around.

4.9 Groundwater Extractions for Non Irrigation Purposes

The USGS has published in a somehow periodic way the approximate rate of groundwater withdrawals by municipality in Puerto Rico thru its “Estimated Water Use in Puerto Rico” publications. The groundwater extractions by municipality in the Salinas to Patillas area for the available years was obtained from these reports done by Torres-Sierra and Avilés (1986) for the years 1980, 81 and 82, Molina-Rivera and Dopazo (1995) for the years 1986 and 87, Dopazo and Molina-Rivera (1995) for the years 1988 and 89, Molina-Rivera (1998) for the year 1995, Molina-Rivera (2005) for the year 2000, and Molina-Rivera and Gómez-Gómez (2008) for the year 2005. Also Kuniansky and Rodríguez (2010) presented a groundwater pumpage estimate for Salinas’s area from 1986 through 2004. The reported daily pumpage rate for the given year was converted to a monthly and yearly value and extrapolated to its neighboring years to fill missing data which produced the yearly groundwater pumpage data shown in figures 36 through 40. These values were used as the groundwater withdrawal input for non irrigation purposes in the developed model of the current study.

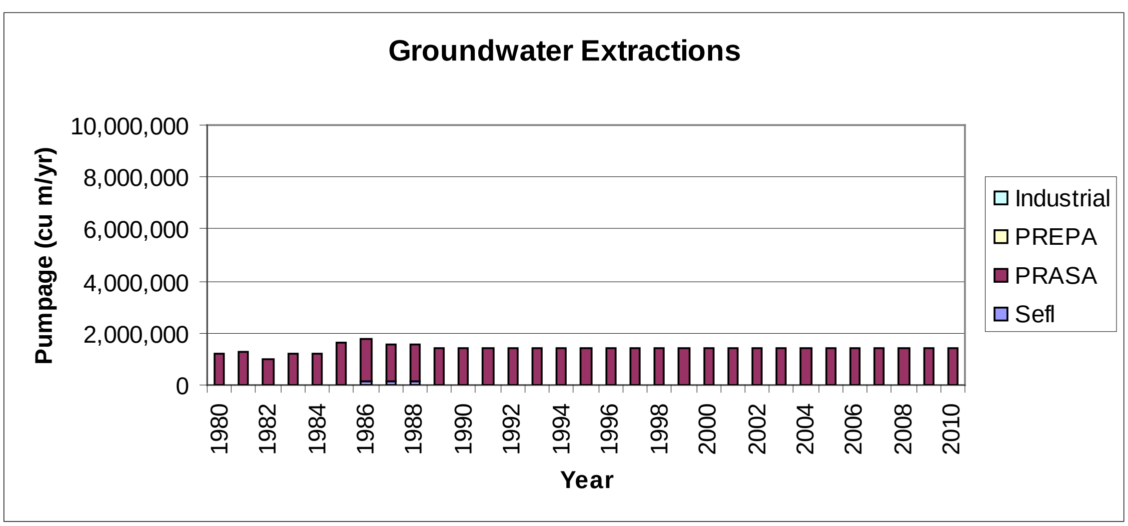

Figure 36. Estimated groundwater pumpage for the municipality of Arroyo. [28]

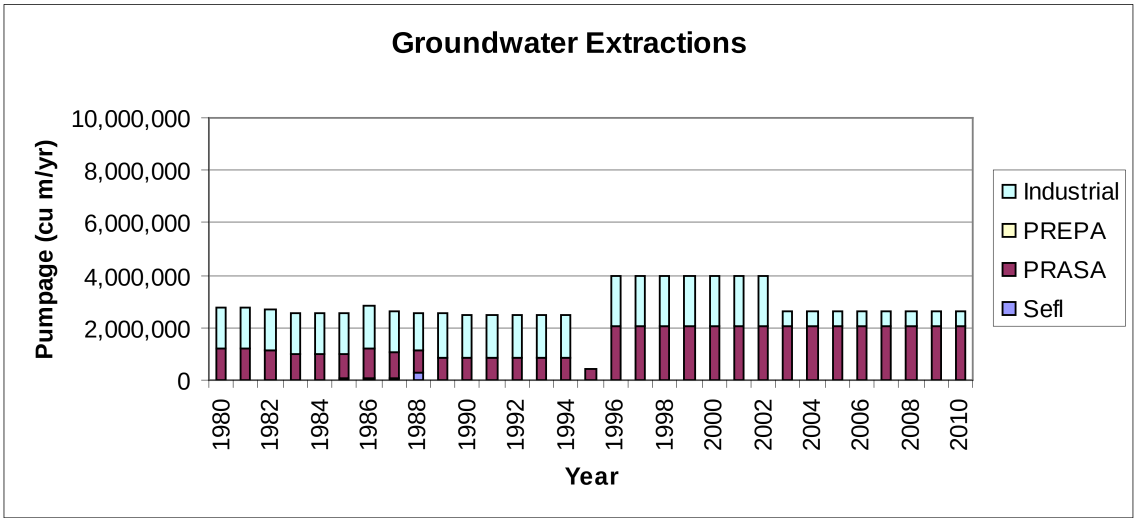

Figure 37. Estimated groundwater pumpage for the municipality of Guayama. [28]

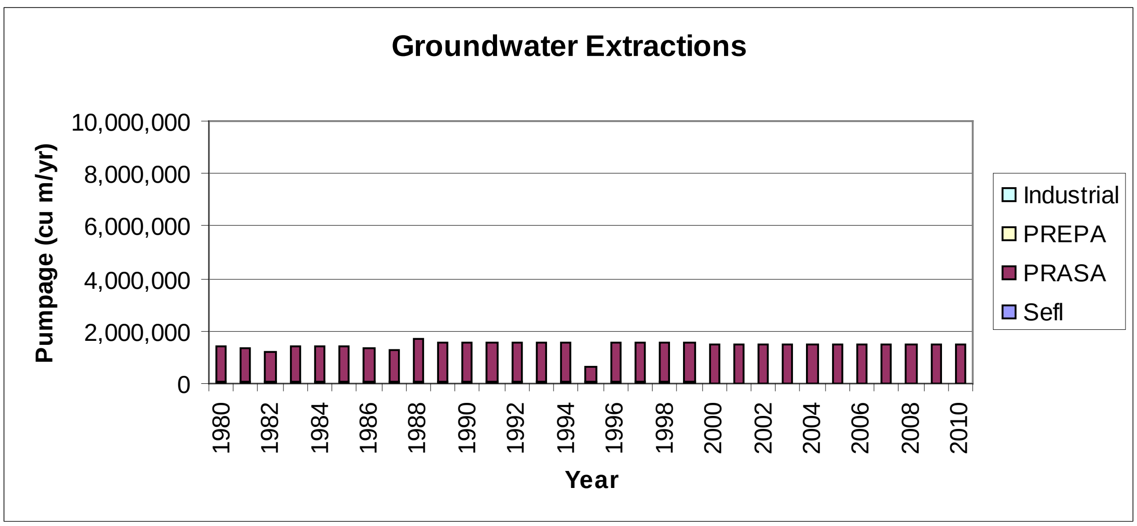

Figure 38. Total estimated groundwater pumpage for the municipality of Patillas. [28]

28 - Converted to annual rates from values reported in publications by: Torres-Sierra and Avilés (1986); Ramos Ginés (1994c); Molina-Rivera and Dopazo (1995); Dopazo and Molina-Rivera (1995); Molina-Rivera (1998); Molina-Rivera (2005); Molina-Rivera and Gómez-Gómez (2008).

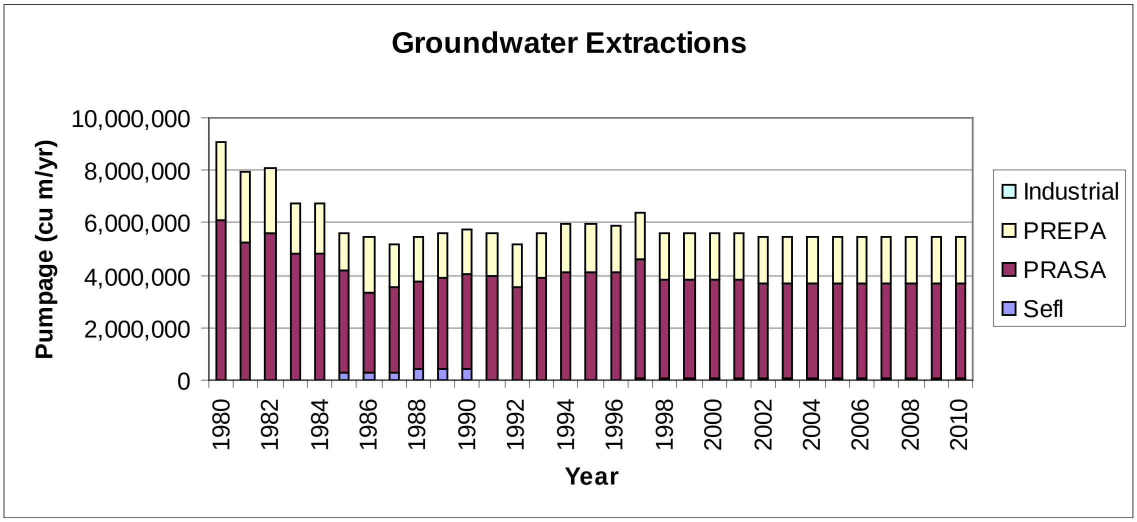

Figure 39. Estimated groundwater pumpage for the municipality of Salinas. [28]

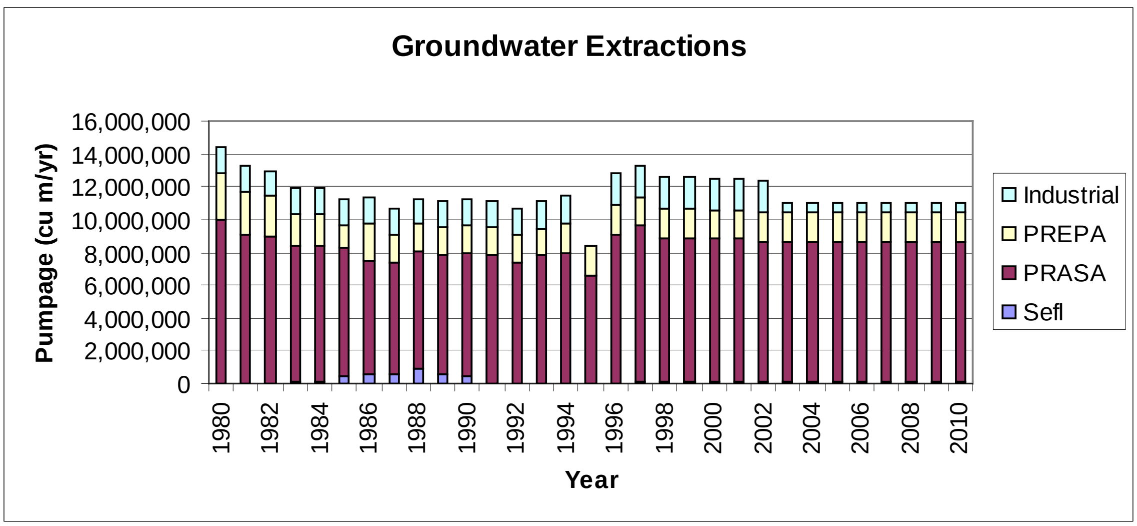

Figure 40. Estimated groundwater pumpage for the Salinas to Patillas study area. [28]

4.10 Irrigated Area

Data on specific annual cropland within the study area is not compiled in a methodic basis and the only institutional source of cropland and irrigated area found is the USDA Agricultural Census (1994, 2000, 2004, 2009), with data for the years 1988, 1992, 1998, 2002, and 2007. The USGS in the “Estimated Water Use in Puerto Rico” publications reported irrigated area estimates based on aerial photos done by Molina-Rivera and Dopazo (1995) for the years 1986 and 87, Dopazo and Molina-Rivera (1995) for the years 1988 and 89, and Molina-Rivera (1998) for the year 1995. Kuniansky and

Rodríguez (2010) published maps, map modifications and area of the agricultural land in Salinas at particular times (1986, 1991 and 2002) within the study period. Moreover, Kennaway and Helmer (2007) published a satellite imagery based map of the land use/land cover of the entire island of Puerto Rico for the year 2000. Ramos and Lugo (1994) published a map of the land use/land cover of the entire island of Puerto Rico for the year 1978 based on aerial photos and land cover maps from where agricultural areas in the Salinas to Patillas region were indentified for that particular year. Also, the irrigated land with irrigation district water can be roughly estimated from the water delivery data obtained from the Guayama irrigation district with dependable results from the beginning of the study period until 1998. Prior to the year 1998 the district quota of irrigation water sold was 2,000 m^3/ha/yr (4 acre-ft per acre-year) of irrigated land per year, after the year 1998 this practice was discontinued.

Data obtained from areal analysis of the 1978 land cover (Ramos and Lugo, 1994), and data from the USGS "Estimated Water Use in Puerto Rico" and from the agricultural census for the four municipalities was used as a base to estimate irrigated area for the missing years (Table 15). For each year of the study period with missing irrigated area, the corresponding area was estimated using linear interpolation between known data by municipality starting with the data from the 1978 Land Cover Map and ending with the data from the 2007 agricultural census. See Figure 41 and Table 17.

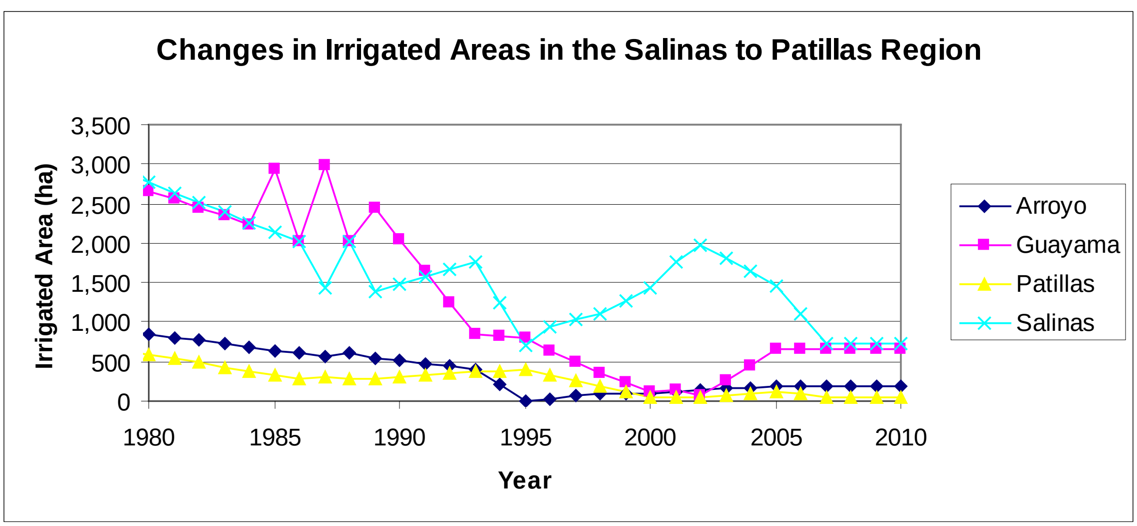

Figure 41. Estimated total irrigated area in hectares (ha).

Table 17. Estimated total irrigated area in hectares (ha).

Year	Arroyo	Guayama	Patillas	Salinas	Total
1977	972[a]	2985[a]	723[a]	3140[a]	7820
1978	931	2878	675	3014	7498
1979	890	2771	627	2888	7176
1980	849	2664	579	2763	6854
1981	808	2556	530	2637	6532
1982	767	2449	482	2512	6210
1983	726	2342	434	2386	5888
1984	684	2235	386	2260	5566
1985	643	2938[h]	338	2135	5243
1986	602[c]	2020[c]	290[c]	2009[c]	4921
1987	561[b]	2981[h]	305[b]	1430[b]	3474
1988	602[d]	2020[d]	290[d]	2009[d]	4922
1989	545[d]	2435[h]	290[d]	1387[d]	2740
1990	509	2036	309	1483	2898
1991	473	1636	328	1578	3056
1992	437	1236	347	1673	3214
1993	401[b]	837[b]	366	1769[b]	3372
1994	201	813	385	1242	2640
1995	0[e]	789[e]	404[e]	715[e]	1908
1996	35	1630	332	946	1903
1997	70	1252	260	1023	1743
1998	105[b]	874[h]	188	1100[b]	1584
1999	100	586	116	1271	1641
2000	95[f]	117[f]	44[f]	1441[f]	1698
2001	115	92	50	1762	2019
2002	135	60[b]	55[b]	1982[b]	2232
2003	155	257	77	1809	2298
2004	175	454	99	1637	2364
2005	195[g]	651[g]	120[g]	1464[g]	2430
2006	195	651	83	1098	2026
2007	195	651	45[b]	732[b]	1622
2008	195	651	45	732	1622
2009	195	651	45	732	1622
2010	195	651	45	732	1622

[a] Based on 1978 Land Cover (Ramos and Lugo, 1994), [b] USDA Agricultural Census (2000; 2004; 2009), [c] Molina-Rivera and Dopazo (1995), [d] Dopazo and Molina-Rivera (1995), [e] Molina-Rivera (1998), [f] Molina-Rivera (2005), [g] Molina-Rivara and Gomez-Gomez (2008), [h] Based on irrigation water deliveries

4.11 Surface Runoff

The Soil Conservation Service (SCS) curve number (CN) method was used to estimate the runoff (RO) from daily precipitation data for the 31 year study period for each modeling area. This method was originally developed by the USDA Soil Conservation Service (SCS); now known as the National Resource Conservation Service

(NRCS), to estimate the depth of a precipitation event that will reach a stream network as runoff. The method was developed in the United States for urban, agricultural and arid areas for four different soil types or hydraulic soil groups A, B, C and D, (Table 18) for “average” antecedent soil moisture conditions (AMC II) and empirically adjusted for dry (AMC I) and wet (AMC III) soil moisture conditions. Hydrologic group A represents soils with the higher infiltration capacity (saturated hydraulic conductivity >36 mm/hr) and hydrologic group D represents soils with the lower infiltration capacity (saturated hydraulic conductivity <1.5 mm/hr, B and C groups represent soils with moderate high (saturated hydraulic conductivity from 15 to 36 mm/hr) and moderate low (saturated hydraulic conductivity from 1.5 to 15 mm/hr) infiltration capacity (USDA-NRCS 1997), respectively. Unfortunately there is not much data on the methodology for the SCS CN development, sites, slopes or storm/runoff intensity used or other data (USDA-NRCS, 1997). Also, some limited CN development was done for Puerto Rico and Hawaii using experimental plots. In Puerto Rico particularly, the CNs were obtained using a relationship between storm and annual precipitation data, and the annual rainfall-runoff data for experimental plots at Mayaguez, Puerto Rico (USDA-NRCS, 1997).

Nonetheless, this is the most used RO estimation method in the world (McCuen, 2004) and it has been used under a variety of conditions with various results where evaluation of its effectiveness for a particular area is recommended (McCuen, 2004).

Table 18. Summary of soil group rating description. [29]

Hydrologic Soil Group	**Characteristics**
A	Deep sand; deep loess; aggregated silts
B	Shallow loess; sandy loam
C	Clay loams; shallow sandy loam; soils los in organic contend, soils usually high in clay
D	Soils that swell significantly when wet; heavy plastic clays; certain saline soils
N	Not rated
Conditions	I: Soils are dry, but not to wilting point. When rainfall is < 36 mm during the previous 5 days. II: Average conditions. When rainfall is between 36 to 53 mm during the previous 5 days. III: Heavy rainfall has occurred within the last 5 days, soil is saturated. When rainfall is > 53 mm during the previous 5 days.

29 - McCuen (2004)

Curve number estimation was performed based on the 1978 land cover (Ramos and Lugo, 1994) for the period between 1980 and 1993 and based on the 2000 land cover (Kennaway and Helmer, 2007) for the period between 1994 and 2010, along with soil type, hydraulic soil group and soil depth obtained from the USDA-NRCS Soil Data Mart. An Excel based model was developed to estimate the runoff for each land cover area and for the entire watersheds using equations 5 and 6.

$$S = (1{,}000/CN) - 10 \qquad 5$$

$$RO = (P-0.2S)^2 /(P+0.8S) \qquad 6$$

Where S is the maximum potential difference between rainfall and runoff at the moment of rainfall initiation (mm), CN is the curve number, which is a proportion of rainfall converted to runoff (McCuen, 2004), obtained for different land covers from the USDA NRCS National Engineering Handbook (USDA-NRCS NEH, 1997), RO is the runoff depth (mm) and P is the precipitation (mm). The CN value was adjusted based on the rainfall depth during the prior five days (antecedent moisture content, AMC) and for slope when the slope average of the modeling area was different than 5% (Sharpley and Williams, 1990; Huang *et al*., 2006; Walker *et al*., 1998; Ebrahimian *et al*., 2009; Setegn *et al*., 2008).

The USDA-NRCS Web Soil Survey data center has published hydraulic ratings for the vast majority of soils (91% of total area) within the study area.

In this study, GIS was used to determine the Curve Number (CNs) based on soil Hydrologic Ratings, land use/land cover maps, AMC and slope. The two land use/land cover maps mentioned, along with the soil data shape files obtained from USDA-NRCS Soil Data Mart for the soils within the modeling areas under study, were used in ESRI (2009) GIS ArcMap to demarcate the curve number for each land use class and soil combination according to their respective hydraulic ratings. To do this, a simple approach was taken:

- all soils within the same hydraulic rating were lumped together or joined into the map,
- then each land cover map was placed independently over the soil hydraulic ratings map,
- through spatial analysis, the land cover areas over each different soil/land hydraulic rating were identified,
- then the different CN values were assigned based on procedure given by the USDA-NRCS NEH (1997),
- using the area and the assigned CNs, the weighted average value of CN for each modeling area and sub-modeling was estimated in Excel,
- the curve numbers for AMC I, II and III were obtained from the USDA-NRCS NEH (1997) according to each land cover and its corresponding soil group,
- finally, the curve number was adjusted for slopes according to Sharpley and Williams (1990).

Several researchers have suggested that the SCS CN method is more appropriate in areas with slopes of 5% or less (Sharpley and Williams, 1990, Huang *et al*., 2006, Walker *et al*., 1998, Ebrahimian *et al*., 2009 and Shimelis *et al*., 2008) rather than for steep slopes. While most irrigated areas within the Salinas to Patillas study area are characterized by slopes less than 5% (Figure 8), pretty much all other land cover areas are under slopes greater than 5%. On the other hand, because of the geographical area where the SCS CN method was developed in the United States, it’s very unlikely that the method is meant for high intensity and low duration storms that characterize Puerto Rico. Adjustment for high intensity storms is unlikely because of the complexity of each different storm, but adjustment of the curve number for steeper or shallower slopes (CN_{sII}) can be done as suggested by Sharpley and Williams (1990) using the equation:

$$CN_{sII} = \frac{CN_{III} - CN_{II}}{3} * [1 - 2 * \exp(-13.86 * slope)] + CN_{II} \qquad 7$$

This slope adjusted curve number is meant to increase the CN (increasing the modeled RO) for slopes grater than 5% and decrease it for slopes smaller than 5% with respect to AMC II, where AMC I and AMC II are re-evaluated for the slope adjusted CN.

Four watersheds were used to verify the relative accuracy of the slope adjusted SCS CN method. Assessment of the slope adjusted SCS CN runoff modeling was performed for the watersheds of the Río Majada and Río Jájome (which are hydraulically connected), Río Lapa, Río Marín and Río Grande de Patillas above the Lago Patillas Dam (Figure 42). These particular watersheds were conveniently chosen for verification purposes because are the only watersheds within the study area which main stream has a USGS stream flow gage with enough data to be used for evaluation purposes.

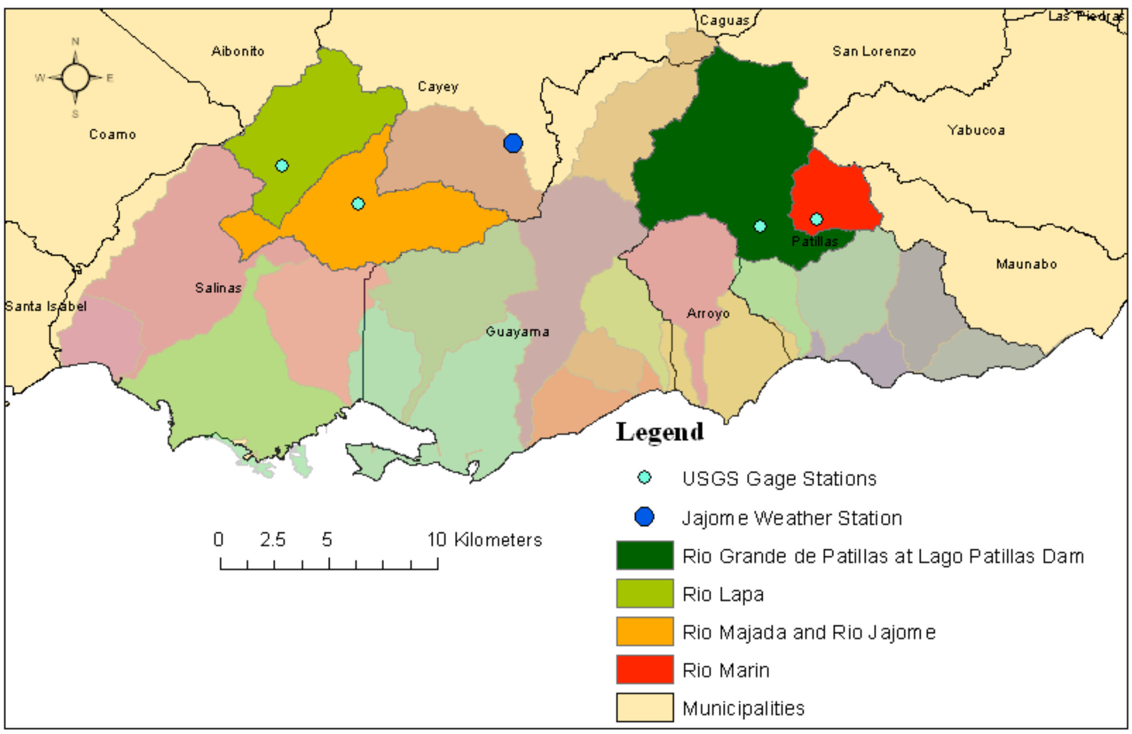

Figure 42. Gaged watersheds within the study area.

Results of a sensitivity analysis of the SCS CN method showed that this model is more sensitive to changes in precipitation than to curve number (CN), which are the two inputs to this model. In the same way, results from a sensitivity analysis of Sharpley and

Williams (1990) CN slope adjustment model showed that the model is more sensitive to CN than to slope.

All four USGS gage stations within the study area are located within the non irrigated watersheds modeling area providing a limited input on how the SCS CN method works within the other four modeling areas (Salinas, Guayama, Arroyo and Patillas) that are located under very different precipitation, slope, soils and land cover conditions. Another drawback is the fact the Jájome Alto weather station; used as input for the SCS CN method, is the only one within the non irrigated watersheds modeling area and is located at one of the highest point in elevation within the study area in the Puerto Rico water divide (see Figure 25). This weather station is located over 600 m above the four USGS gage stations and about 14 and 12 km northwest of the Río Marin and Río Grande de Patillas gage stations respectively and about 11 and 8 km northeast from the Río Lapa and Río Majada gage stations. The Jájome Alto weather station may not be as representative of the actual precipitation and precipitation distribution of the watersheds used for modeling, but counts with the best available precipitation data, therefore its data was used as the precipitation input for the SCS CN method.

Ultimately, runoff estimates based in the SCS CN method were compared with daily separated runoff from stream flow data from the USGS WaterWatch webpage for Río Marín, Río Grande de Patillas above the Lago Patillas dam, Río Majada and Río Lapa gage stations. The daily runoff-base flow separation was performed using the Web-based Hydrograph Analysis Tool, WHAT (Lim and Engel, 2004 and Lim et al., 2005). WHAT is a base flow/runoff separation system developed in Purdue University as a universal tool to separate base flow/runoff from the USGS Water Watch network by incorporating 3 different digital filter methods previously developed and validated using 50 gauging station in Indiana (Lim et al., 2005).

The process to compare RO results from the two sources (SCS CN and USGS gauge measurements) was as follows. Base flow was separated from stream flow with the purpose of estimating runoff (RO) using WHAT which retrieves the data directly from the USGS Water Watch webpage. Then, the estimated RO data derived from stream flow in ft^3/s (as published by USGS Water Watch, as well as the results from WHAT) was converted to flow depth using Equation 8:

$$D_f\left(\frac{mm}{d}\right) = \frac{f_m\left(\frac{ft^3}{s}\right) * 12\left(\frac{in}{ft}\right) * 25.4\left(\frac{mm}{in}\right) * 3600\left(\frac{s}{hr}\right) * 24\left(\frac{hr}{d}\right)}{43560\left(\frac{ft^2}{acre}\right) * A(acre)} \qquad 8$$

where f_m is the mean daily runoff, and A is the area of influence published along the USGS data (USGS WaterWatch).

Several years of precipitation and direct runoff for stream flow data (data from 3 years for Río Marin, 12 years for Río Grande de Patillas, 10 years for Río Majada and 7 years for Río Lapa) were used to find out if effectively the slope modified SCS CN was a better fit for RO estimation then the standard SCS CN method in the study area. It was found that estimates from the slope modified SCS CN produced the smaller Sum of Squared Errors when comparing it to monthly direct runoff from the USGS gage stations and the standard SCS CN method. This conclusion was based on the sum of daily runoff estimates over a month from the SCS CN method and its adjustment for slopes versus the total runoff in the same month that was estimated from USGS stream flow data using the WHAT application for base flow/runoff separation.

The SCS CN based on AMC and under slope adjustment, is better tool than the standard CN methods for watersheds with mean slopes different than 5% as suggested by Sharpley and Williams (1990). The analysis was based on the following slope analysis results:

- Rio Marin: 37.5% mean slopes
- Rio Grande de Patillas above Patillas Dam: 38.1% mean slopes
- Rio Majada: 31.5% mean slopes
- Rio Lapa: 39.3% mean slopes

Appendix I present the results of RO estimates and measurements, and precipitation for the 3 years between 2005 and 2007. The method chosen for RO/infiltration estimation produced fair results for most months considering the assumptions and limitations of the model.

Some of the errors that the SCS CN method and the slope adjustment model might introduce to the RO estimations may come from:

1. Flaws in the data. There are months where registered RO was very similar or greater than registered precipitation, which is unlikely. In this case, either the precipitation or the stream flow data introduced an error.
2. Precipitation data is given as depth (mm/d) and stream flow data is given as daily mean flow (English units of ft^3/s) where errors can be introduced in the conversion factor process.
3. SCS CN method is meant for agricultural watersheds in the United States that are not characterized by steep slopes and shallow soils, nor the high intensity and low duration storms as the mountainous areas in the south facing hills of the Puerto Rico Central Mountain Chain, where a large part of the study area is located.
4. There are no CN values for much of the land covers under the conditions present in the study area, CN values for the most similar cover or condition was used.
5. Intensity and duration of the storm is not represented by the measurement of daily precipitation depth. Where a high intensity and low duration event might produce higher runoff than a lower intensity and longer duration event of similar precipitation depth.
6. Weather stations, even when within the watershed boundaries, not necessarily represent the actual precipitation depth distribution over the watershed.

4.12 Land Use/Land Cover

Two land cover maps were used to estimate the appropriate hydrologic soil cover for each modeling area. For the first part of the study period (1980 to 1993) the land cover map used is the one published by Ramos and Lugo (1994), as shown in Figure 43 and Table 19, which is based on aerial photos taken in the years 1977 and 1978. Before

1993 the Salinas to Patillas area was characterized by large fields of sugarcane under flood and furrow irrigation, this conditions marked the two periods of study. The land cover produced by Kennaway and Helmer (2007), in Figure 44 and Table 20, was used to generate an estimated hydrologic soil cover for the years between 1994 and 2010 when there was no more sugarcane and surface irrigation had considerably depleted.

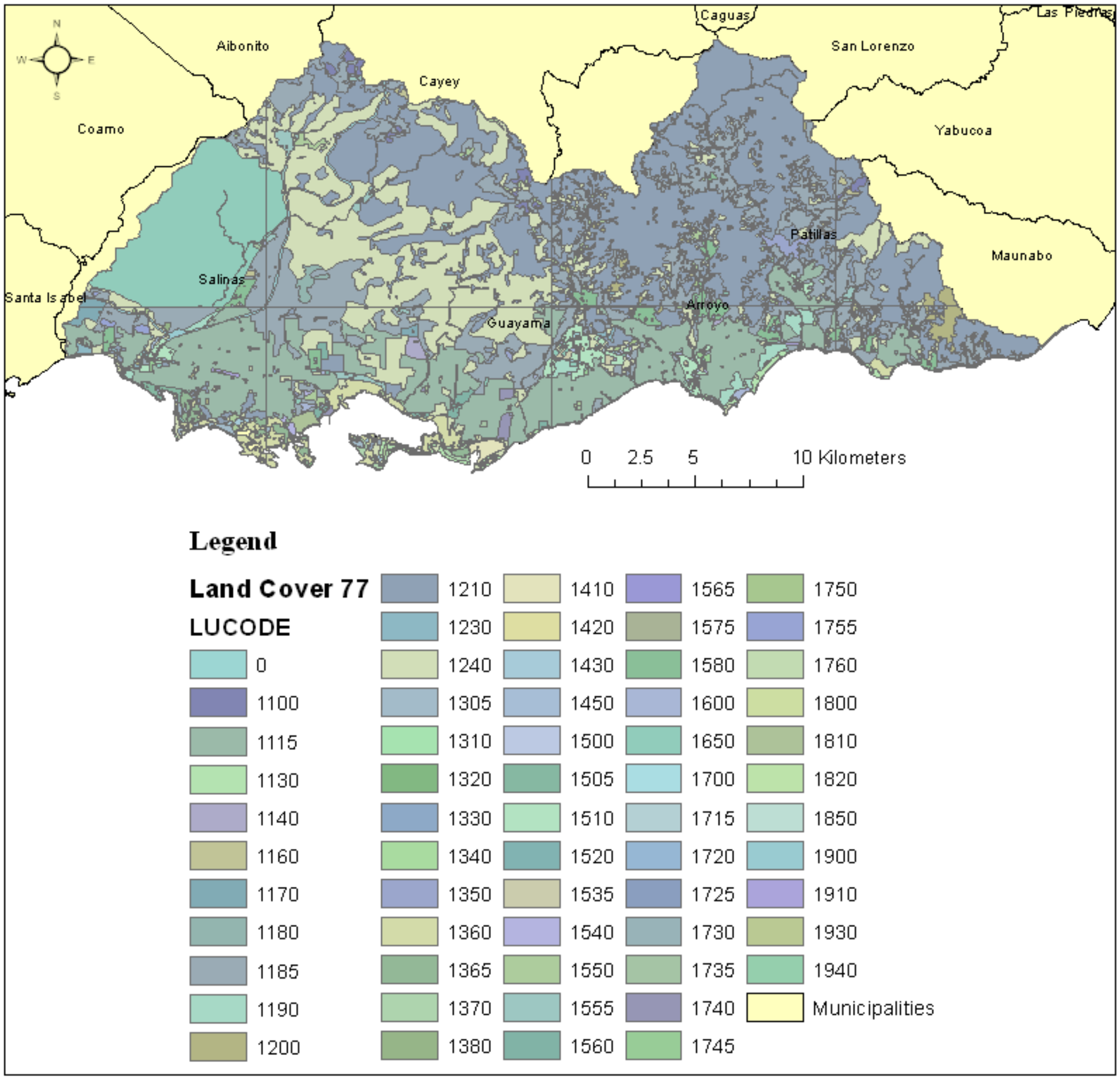

Figure 43. 1977-78 Land use/Land cover for the Salinas to Patillas area.[30]

30 - Ramos and Lugo (1994)

Table 19. 1977-78 Land Cover descriptions for the Salinas to Patillas Area. [30]

Code	Land Used	% of Total Area
	Agriculture	**33.03**
1115	Sugarcane	
1140	Plantains and Bananas	
1170	Specialize Farms	
1180	Active but Undefined Agricultural Lands	
1185	Pastures	
1190	Inactive Agriculture	
	Forest Land	**47.99**
1210	High Density Trees, Medium Size, Small Canopy	
1240	Shrubs and Scrubs	
	Water Bodies	**3.65**
1305	Lagoon	
1320	Protected Coastal Waters	
1330	Channels Subject to Tide Flows	
1340	River	
1350	Artificial Water Body (+- 1 acre)	
1360	Mangrove	
1370	Saltpeter	
	Residential Areas	**4.89**
1510	Urban, High Intensity	
1540	Urban Under Construction	
1550	Rural, Low Intensity	
1555	Rural, Medium Intensity	
1560	Rural, High Intensity	
1565	Residential Rural Fringe	
1570	Temporal Housing in Rural Zone	
1580	Parcels	
	Public Use	**8.70**
1600	Recreational areas	
1650	All Types	
	Commercial, Industrial	**0.66**
1715	Commercial Fringe	
1720	Hotel, Motel	
1730	Commercial Storage	
1735	Industrial Light	
1740	Industrial Heavy	
1750	Roads	
	Communications	**0.16**
1810	Electrical Plant	

The 1977-78 land use/land cover map was created from aerial photography of the actual soil cover during those two years. Covers given in this map were compared to a 1994 aerial photo (the oldest aerial photo for the area available in Google Earth, 2009) using ESRI (2009) GIS software. From this comparison it was decided that this land use/land cover map is sufficiently accurate and had enough detail for the purpose of this project. Personal communication (2011) with Olga Ramos, from the USDA Center for Tropical Forestry and one the authors of this map, confirmed the appropriateness of this tool for the intended purpose. On the other hand, the same comparison was done for the 2000 land use/land cover map by Kennaway and Helmer (2007) with an aerial photo from the year 2001. It was found that the level of detail and accuracy provided by this map is lower than the 1978 land use/land cover map. For this study, verification and slight adjustment of land cover with a 2001 aerial photo was performed for each modeling area in order to better identify the appropriate CNs for RO estimation.

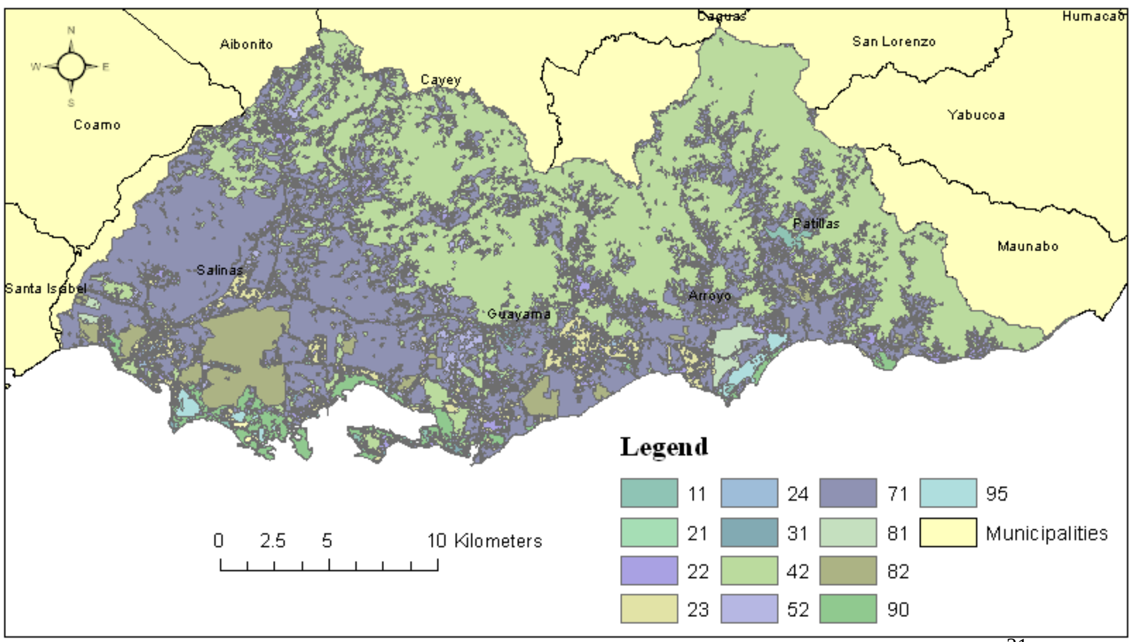

Figure 44. Land Cover for the year 2000 for the Salinas to Patillas Study Area. [31]

31 - Kennaway and Helmer (2007)

Table 20. Land Cover description for the Salinas to Patillas Area. [31]

Land Cover	**Code**	**Description**	**% of Total Area**
Open Water	11	All areas of open water, generally with less than 25% cover or vegetation or soil	0.6
Developed, Open Space	21	Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes	1.1
Developed, Low Intensity	22	Developed, Low Intensity -Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units.	4
Developed, Medium Intensity	23	Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single-family housing units.	3.4
Developed, High Intensity	24	Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to100 percent of the total cover.	0.4
Barren Land (Rock/Sand/ Clay)	31	Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.	0.3
Evergreen Forest	42	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage	44.4
Shrub/ Scrub	52	Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.	3.0
Grassland/ Herbaceous	71	Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.	34.9
Pasture/ Hay	81	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.	0.7
Cultivated Crops	82	Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total vegetation. This class also includes all land being actively tilled.	4.2
Woody Wetlands	90	Areas where forest or shrub land vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	2.2
Emergent Herbaceous Wetlands	95	Areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.	0.8

4.13 Daily Crop Water Demand Model

Actual or crop evapotranspiration (ET_c) was estimated using Equation 9 (Allen *et al*., 1998):

$$ET_c = K_c * ET_0 \tag{9}$$

where K_c is the land cover evapotranspiration coefficient, and ET_0 (mm/day) is the reference evapotranspiration estimated using the Hargreaves and Samani (1982) method. Table 21 presents the cover coefficients (K_c) published by Prieto (2007) and Allen *et al*. (1998) that was utilized to estimate the weight average ET_c for each modeling area of the current study.

The Hargreaves and Samani (HS) method is one of the simplest methods to estimate reference (also referred as potential) evapotranspiration or ET_0. This is a model developed based on the average characteristics of weather data from 56,000 stations around the world. Allen *et al.* (1998) and Harmsen *et al*. (2010) recommend this method when solar radiation and wind speed data is missing. Harmsen *et al*., (2010) suggested that this approach is an accurate method to estimate ET_0 in Puerto Rico. The Hargreaves-Samani method takes the form:

$$ET_0 = 0.0023\ R_a * [T + 17.8] * (TD)^{0.50} \tag{10}$$

Where:

ET_0 is the reference evapotranspiration in mm/day

0.0023 is the model's empirical adjustment (constant)

R_a is the average extraterrestrial radiation in mm/ day.

T is the average daily temperature, °C. $T = \frac{T\max - T\min}{2}$

TD = Difference between maximum and minimum temperatures, °C.

Table 21. K_c values for different land covers in Puerto Rico. [32]

Land Cover	**K_c**
Wetland, mangrove	1.2
Urban	0.3
Sand, rock	0.1
Forest	0.85
Pasture	0.9
Agriculture	1

Solar radiation (R_a) data, required for the Hargreaves and Samani method, was obtained from the FAO 56 publication (Allen *et al.*, 1998), which averages solar radiation for a 30 year period for each latitude and where the use of interpolation between latitudes is recommended (Allen *et al.*, 1998). The ET_0 for each modeling area was estimated based on R_a estimated from the latitude at which its weather station is located. The maximum and minimum temperatures were obtained from the already mentioned weather stations. Results from a sensitivity analysis on the Hargreaves and Samani model showed that the model's least sensitive parameter is the minimum temperature. Then is followed by the empirical adjustment, the solar radiation, and having the maximum temperature as the most sensitive factor.

The Hargreaves and Samani model was calibrated in a monthly basis using the Penman-Monteith (PM) model based on data from the nearby Fortuna weather station as recommended by Allen *et al.* (1998). Calibration of the Hargreaves Samani model resulted in a slight change to the model's empirical adjustment, changing it from 0.0023 to 0.00237, and the resulting calibrated Hargreaves and Samani model takes the form:

$$ET_0 = 0.00237\ Ra * [T + 17.8] * (TD)^{0.50} \qquad 11$$

Results of the calibration process are presented in Figure 45 where the results from calibrated Hargreaves and Samani model is presented against results from the Penman-Monteith model using data from the Fortuna weather station.

32 - Prieto (2007) and Allen *et al.* (1998)

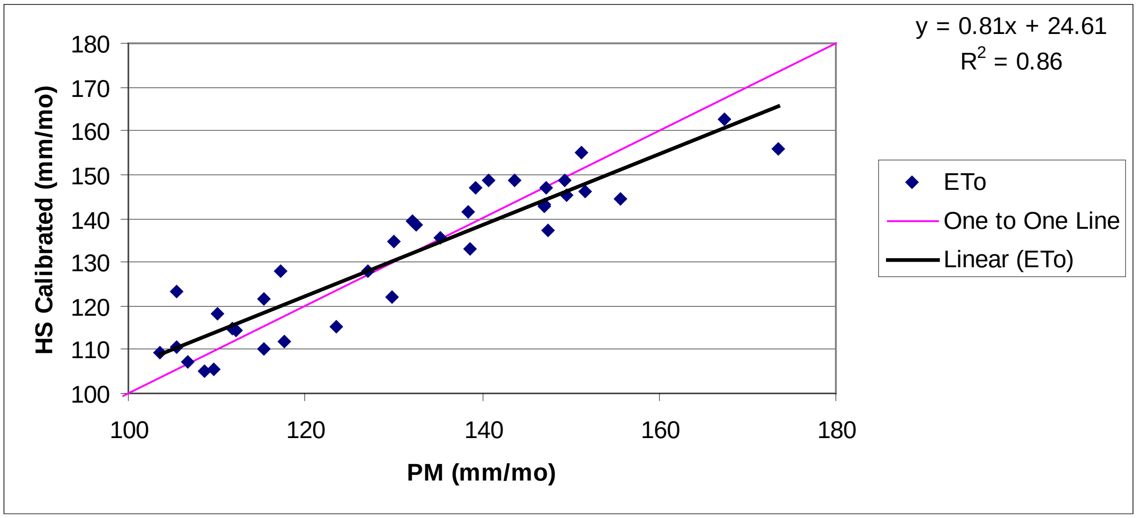

Figure 45. Hargreaves and Samani (HS) calibration results.

Reference evapotranspiration estimates from the Hargreaves and Samani model were validated using pan evaporator data from Aguirre weather station as recommended by Allen *et al*. (1998), where the reference evapotranspiration estimates for this station were compared to evaporation measured data from a nearby pan evaporator for periods of 23 days. However, pan evaporator adjustments were first performed according to Allen *et al*. (1998).

$$ET_0 = Kp*E_{pan} \qquad 12$$

where ET_0 is the reference evapotranspiration [mm/day], K_p is the pan coefficient, 0.79 in this case, and E_{pan} is the pan evaporation [mm/day].

Results of the validation process are presented in Figure 46 where the results from calibrated Hargreaves and Samani model based on data from the Aguirre weather station is set against adjusted pan evaporator data from the same station.

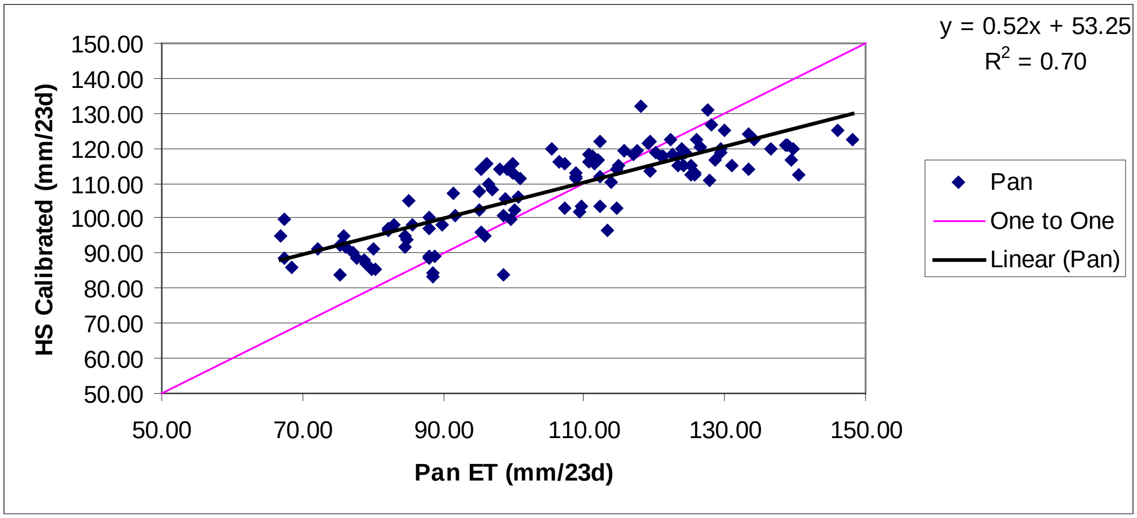

Figure 46. Hargreaves and Samani validation results.

The Hargreaves and Samani (HS) method was used because of the unavailability of wind speed and terrestrial radiation data from local pyronometers and/or remotely sensed data that is necessary for the Penman-Monteith (PM) method within the study area. The Penman-Monteith method is recommended as the standard to estimate ET_0 in scientific work with the Hargreaves and Samani method as its alternative when missing data (Allen *et al*., 1998).

For specific details on the calibration and validation procedure, its results and conclusions refer to Appendix II.

4.14 Daily Soil Moisture Budget Model

It was assumed that percolation past the root zone (Perc) occurs when the water depth that enters the soil exceeds the soil moisture capacity within the effective root depth and that this water results on aquifer recharge. For the vast majority of plants, the water absorption mostly occurs within the 80% of the root zone depth closer to the surface which is called the effective root depth.

The crop soil moisture capacity (SM_{max}) was estimated as the product of the weighted average effective crop rooting depth per modeling area and a weighted average field capacity in the same modeling area (Equation 13). Rooting depth and effective root zone depth were obtained from James (1988) and Allen *et al*. (1998) depending on land cover, and were adjusted for soil depth, which could be a limiting factor for rooting depth, especially on steep slopes. Weighted average soil depth per modeling area was estimated from the NRCS Soil Data Mart.

The crop soil moisture capacity is:

$$SM_{max} = \theta * L \qquad 13$$

where SM_{max} is the soil water content at field capacity for the determined cover, θ is the weighted average field capacity, and L is the weighted average rooting depth or the weighted average soil depth, whichever is smaller. If the effective root zone depth, which is the root depth where the plants absorb 80% of their water, is limited by the soil thickness, then the soil thickness or depth is to be used instead of the rooting depth. In other words, to account for soil thickness limitations, if soil thickness is greater than root zone depth, then effective root zone depth will be equal to the root zone depth. On the other hand, if soil thickness is less than root zone depth, the soil thickness would represent the effective root zone depth.

Perc (deep percolation) was estimated from equation:

$$Perc = SM_2 - SM_{max} \qquad 14$$

where SM_{max} is the soil water content at field capacity and SM_2 is the current day soil moisture content, as defined previously in Equation 1. Soil field capacity was estimated from data derived from the NRCS Soil Data Mart as the maximum available water within the first meter of soil for each soil surveyed in each modeling area, where the weight averaged soil depth was assumed as a single value for each modeling area. If Perc resulted to be less than 0, then Perc is assumed to be zero and the estimate of SM_2 from Equation 1 is used. However, if Perc is greater than or equal to zero, then SM_2 is equal to

SM_{max} for the next day and Perc for the present day is the value obtained from Equation 14.

The soil hydraulic conductivity is assumed to be high enough for the soil moisture to be uniformly redistributed and the entire soil column within the root zone to be drained in a 24-hour period. Ramos-Ginés (1994c) stated that most soils in the southeastern coastal plain (Santa Isabel to Patillas area) have a hydraulic conductivity between 1 and 5 mm/hr.

For estimating areal evapotranspiration coefficients (Table 21), depletion factor (Table 22) and the effective root zone depth (Table 22), it was assumed that forest, pastures, grassland, brush and scrub, fallow, wetlands, mangrove, emergent wetlands, sugarcane, plantains and vegetables represent the actual vegetation covering each modeling area. The plant or crop depletion factor (AD) is the maximum water depletion that can occur within the root profile before the plant or crop reaches its wilting point. The wilting point ($WP = SM_{max}*AD$) is the point where plant water loss through evapotranspiration reaches higher rates than plant root water absorption. This occurs when tension in the soil is greater than in the roots absorption capacity, and has crop yield loss as consequence. In the other hand, the maximum allowable depletion (MAD) is when the plant available water in the soil reaches a negligible point, causing permanent damage to the plant or crop.

Table 22. Effective root depth and depletion factors for different land covers. [33]

Land Cover	**Effective Root Depth (m)**	**Depletion Factor (AD)**
Forest	1	0.2
Pastures	0.8	0.4
Grassland	0.3	0.2
Sugarcane	1.3	0.35
Plantains	0.6	0.65
Vegetables	0.8	0.60
Fallow	0.3	0.2
Mangrove Wetlands	1	0.6
Emergent Wetlands	0.8	0.6
Brush and Scrub	0.8	0.2

33 - Allen *et al.* (1998)

A lumped soil depth, crop coefficient, maximum available soil moisture and plant water depletion was used for this study because of the lack of spatially distributed crop data; therefore, it was assumed that a single value for each one of these factors apply to each modeling area. Commonly, farmers and irrigation managers strive to irrigate their fields when the plant available water is between 50 and 75 percent.

4.15 Irrigation Scheduling Model

The last two sections were incorporated into an irrigation scheduling model that accounts for soil moisture losses through evapotranspiration and deep percolation and to estimate daily irrigation requirements for each modeling area. For each day in the 31 year study period, precipitation minus runoff was added to initial soil moisture to determine available soil moisture for the plant or crops at the beginning of the day:

$$SM_2 = SM_1 + P - RO \qquad 15$$

where SM_2 and SM_1 are the available soil moisture for the present and previous day, respectively, P is the precipitation and RO is the runoff.

In agricultural areas, irrigation (Equation 16) was assumed to be applied the day before the soil moisture content (SM_2) reaches wilting point for the crop. Only effective irrigation will recharge the soil moisture content (Equation 17).

$$I = SM_{max} – SM_1 \qquad \text{applied when } SM_2 < (SM_{max} * AD) \qquad 16$$

$$I_e = I - ET_c \qquad 17$$

When soil moisture capacity reaches zero it was assumed that ET_c stop, maintaining the soil moisture at a zero value. If there is no soil moisture for uptake, most plants would enter a stress stage closing their stomas and reducing ET_c to a negligible point.

Daily plant water demand can only be satisfied when the SM_2 is greater than the wilting point for a particular day. The portion of the daily crop water demand that is not satisfied by soil moisture was also calculated for each day as:

$$U = ET_c - SM_2 \qquad 18$$

where U is the unmet water demand for each modeling area on the present day.

4.16 Stream flow

Stream flow data was an important asset to estimate base flow, event flows, and seepage. There are 13 USGS gage stations in the area. Table 23 presents these 13 water flow stations, seven of which are located on the Patillas-Guamaní irrigation canals (5 in the Patillas canal and two in the Guamaní canal) and six along water bodies in the study area. Mean daily discharge data files were retrieved from the USGS National Water Information System web server also known as the USGS WaterWatch.

Table 23. USGS Gage Station within the Salinas to Patillas Area. [34]

USGS Gage Station	Location
50093115	CANAL DE PATILLAS AT INTAKE 123, SALINAS
50093110	CANAL DE PATILLAS AT INTAKE 113 SALINAS
50093095	CANAL DE PATILLAS BLW EL LEGADO INTAKE
50093085	CANAL DE PATILLAS BLW AES INTAKE AT GUAYAMA
50093078	CANAL DE PATILLAS BLW GUAYAMA FILTRATION PLT
50095000	CANAL DE GUAMANÍ OESTE AT HWY 15 GUAYAMA
50094545	CANAL GUAMANÍ AT CARITE FOREBAY
50039995	LAGO CARITE AT SPILLWAY
50100450	RÍO MAJADA AT LA PLENA
50100200	RÍO LAPA NR RABO DEL BUEY
50093120	RÍO GRANDE DE PATILLAS BLW LAGO PATILLAS
50092000	RÍO GRANDE DE PATILLAS NR PATILLAS
50093000	RÍO MARIN NR PATILLAS

4.17 Base flow and Seepage

Stream base flow, and more importantly, seepage, is a significant factor on groundwater-surface water interactions. McClymonds and Díaz (1972), Ramos-Ginés (1994b and 1994c), Quiñones-Aponte *et al.* (1997) and Kuniansky and Rodríguez (2010)

34 - USGS WaterWatch

among others stated that most; if not all, of the base flow generated in the mountainous areas eventually turns into seepage in the alluvial valley as a source of recharge for the Southern Aquifer. Quiñones-Aponte *et al.* (1997) estimated the mean annual base flow for the Río Majada, Río Lapa, Río Guamaní, Quebrada Melanía, Río Nigua de Arroyo, and Río Grande de Patillas to be 77 mm/yr approximately (Table 24). Using WHAT application for base flow/runoff separation, base flow from the Río Majada and Río Lapa was estimated to be 103 and 72 mm/yr respectively which are similar results to those from Quiñones-Aponte *et al.* (1997).

Kuniansky and Rodríguez (2010) estimated annual base flow for Río Majada and Río Lapa from 1989 through 2002 using the base flow/runoff separation software PART (Rutledge, 1993), while the years 1986, 87, 88, 2003 and 04 were estimated based on linear regressions of annual rainfall data from the Jájome Alto weather station. Results from annual base flow separation from PART obtained from Kuniansky and Rodríguez (2010) are plotted against the results from WHAT for the Río Majada and Río Lapa in Figures 47 and 48 respectively. For the Río Majada both base flow separation models provided very similar results, in the opposite side, base flow separation for the Río Lapa from WHAT resulted in lower annual base flow than from PART. Judging by the base flow estimates from Quiñones-Aponte *et al.* (1997) and Kuniansky and Rodríguez (2010), WHAT produces better base flow estimates for the Río Majada than from the Río Lapa.

Table 24. Area out/above alluvium, precipitation and base flow data. [35]

Stream	**Area (m^2)**	**Precipitation (mm/yr)**	**Base flow (mm/yr)**
Río Majada	43,253,000	1651	76.39
Río Lapa	25,693,000	1270	76.47
Río Guamaní	33,152,000	1778	78.12
Quebrada Melanía	11,914,000	1321	74.96
Río Seco	29,526,000	1270	75.61
Río Nigua de Arroyo	15,022,000	1651	77.28
Río Grande de Patillas	75,110,000	2159	77.28

35 - Quiñones-Aponte et al. (1997) and Calvesbert (1970)

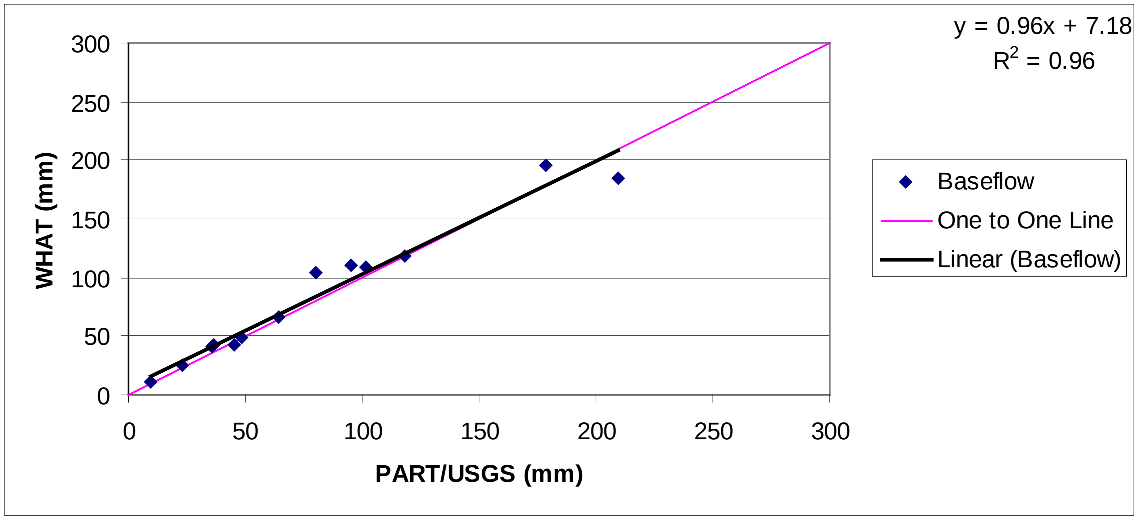

Figure 47. Results from annual base flow separation from PART obtained from Kuniansky and Rodríguez (2010) vs results from WHAT for the Río Majada.

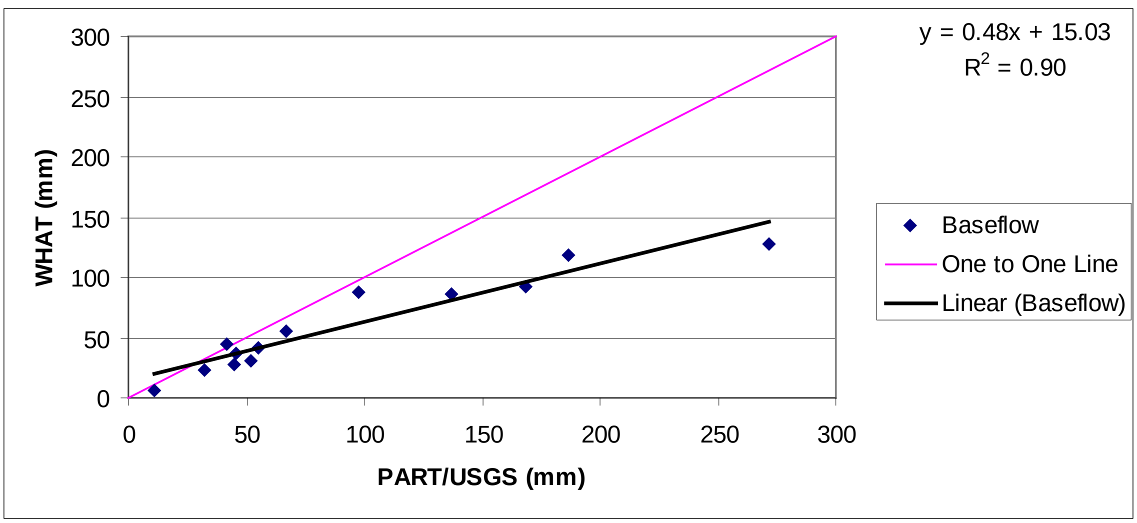

Figure 48. Results from annual base flow separation from PART obtained from Kuniansky and Rodríguez (2010) vs results from WHAT for the Río Lapa.

Kuniansky and Rodríguez (2010) estimated the infiltration to the aquifer from the other streams in their study area (Río Jueyes and Río Seco, Quebrada Honda, Quebrada Coquí, and Quebrada Cimarrona) for 1986 to 2004 based on the assumption that the base flow, expressed in depth per year, is half the average base flow over the Río Lapa and Río Majada drainage basins. This was done under the assumption that the altitudes of the drainage areas of the other streams in the study generally are lower than those of the Río Lapa and the Río Majada, and under the hypothesis that these watersheds located at lower drainage areas that may only receive half as much rainfall as the mountains, as indicated on areal precipitation maps (Figure18).

Following the same principle used by Kuniansky and Rodríguez (2010), for the Salinas to Patillas study area, monthly base flow data for the Río Majada was estimated using linear regression between the Jájome Alto weather station and the estimated base flow from the Río Majada USGS gage station (Figure 49) for the years prior to 1989 (1980 through 1988).

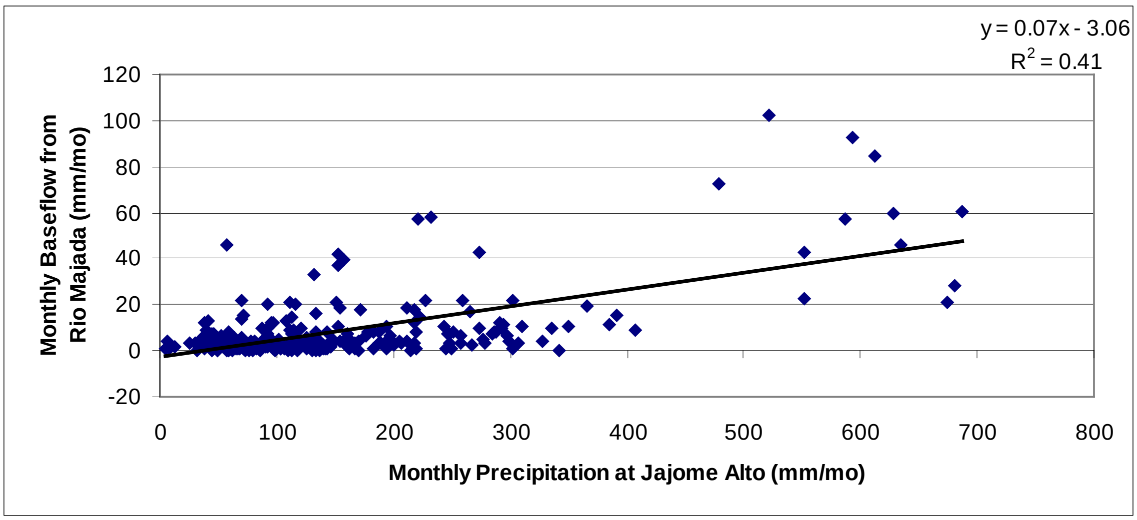

Figure 49. Monthly precipitation at Jájome Alto weather station plotted against estimated base flow from the Río Majada USGS gage station.

The ungaged watersheds within the study area are: from west to east, Río Nigua de Salinas, Quebrada Aguas Verdes, Río Seco, Río Guamaní, Quebrada Branderi, Quebrada Corazón, Río Nigua de Arroyo, Río Grande de Patillas and Río Chico. Base flow for these watersheds was also estimated following the same principle used by Kuniansky and Rodríguez (2010) where it was also assumed that all base flow produced above the alluvium extend turns into aquifer recharge once it reached the mid and lower alluvium. The difference is that instead of assuming the unknown base flow depth to be half base flow depth from the Río Majada and Río Lapa, it was assumed that the monthly base flow depth for each of these ungaged watersheds equals the base flow from the Río Majada multiplied by the monthly precipitation ratio between the Jájome Alto weather station and the nearest weather station to the watershed. This assumption was taken under the premise that watersheds between the Jájome Alto and Aguirre weather stations (within Salinas), between the Jájome Alto and Guayama weather stations (within the Guayama-Arroyo area), and between the Jájome Alto and Patillas weather stations (within Patillas) have similar land cover, slopes and precipitation-runoff patterns.

A monthly precipitation ratio was used to adjust for differences in monthly base flow depth between the Río Majada and the ungaged watersheds in order to account for the differences in precipitation between watersheds. These also add a physical factor to the base flow estimation. The process used is as follow: monthly base flow data from Río Majada in mm/mo was multiplied by the ratio between the monthly precipitation at the Jájome Alto weather station and the nearest weather station for the determined ungaged watershed, presented in Table 25, to obtain its base flow in mm/mo, then this base flow was multiplied by the watershed area outside the alluvium to produce base flow in m^3/mo after using the corresponding conversion factor. This was done under the assumption that all base flow within a watershed is produced in the area outside the alluvium extend.

Table 25. Ungaged watersheds with its estimated area upstream of the alluvium expected to produce base flow and the nearby weather station to be used along with the Jájome Alto weather station to estimate a ration of monthly precipitation.

Ungaged Watershed	**Area out of Alluvium (m^2)**	**Near Weather Station**
Río Nigua de Salinas	43,856,000	Aguirre
Quebrada Aguas Verdes	12,759,000	Aguirre
Río Seco	23,766,000	Aguirre
Río Guamaní	25,040,000	Guayama
Quebrada Branderi	6,067,000	Guayama
Quebrada Corazón	6,174,000	Guayama
Río Nigua de Arroyo	16,669,000	Patillas
Río Chico	14,608,000	Patillas

Using this method, the total estimated monthly seepage from the ungaged streams range from 0 to 588,650 m^3/d from 1980 to 2010, with an average of 28,960 m^3/d. These estimates may be conservative because they are derived from base flow data, and according to Kuniansky and Rodríguez (2010) estimated average daily base flow was equaled or exceeded on the Río Majada gage station over 20 percent of the days within the period between 1989 and 2002. The average estimated infiltration compared to the previous estimates of McClymonds and Díaz (1972) and Kuniansky and Rodríguez (2010) are presented in Table 26.

Previous studies have confirmed that streams in the study area are contributors to ground water recharge as well as the irrigation canals. In the case of the irrigation canals, Quiñones-Aponte *et al.* (1997) and Kuniansky and Rodríguez (2010) stated that the Patillas-Guamaní network of irrigation canals are direct contributors to groundwater recharge to the south coast aquifer. They speculated the maximum canal losses are constrained to be less than 4,900 m^3/d under their modeling conditions while their results stipulated an average groundwater recharge of 3,975 m^3/d from the irrigation canals and the Melanía reservoir. Kuniansky *et al.* (2004) estimated that 3,130 m^3/d of water from the Juana Díaz irrigation canal recharges the aquifer in the Santa Isabel area while Ramos-Ginés (1994a) estimated aquifer recharge from seepage of water through Juana Díaz canal to be 15,900 m^3/d or 30 percent of the water diverted for irrigation in his study area.

Table 26. Average estimated infiltration compared to the previous estimates. [36]

Ungaged Watershed	**USGS (m^3/d)**	**Estimated (m^3/d)**
Río Nigua de Salinas	19,695	7,494
Quebrada Aguas Verdes		2,180
Río Seco	2,985 and 6,116	4,061
Río Guamaní	7,095	5,915
Quebrada Branderi		1,433
Quebrada Corazón		1,459
Río Nigua de Arroyo	3,181	3,646
Río Chico		3,195

The Guayama Irrigation District of PREPA used to estimate losses from the irrigation water distribution and conveyance. Although the methodology for this estimation is unknown, it is still an important component of the water balance of the area as it contributes to groundwater recharge. Estimates of water loss (seepage and evaporation) through the irrigation canals done by PREPA was obtained for the years 1980, 84, 91, 92, 93, 94, 95, 96 and 97 (Guayama Irrigation District, 2010) for the Patillas, Guamaní Este and Guamaní Oeste irrigation canals. This irrigation losses for the

36 - McClymonds and Díaz (1972) and Kuniansky and Rodríguez (2010)

entire system was translated to irrigation losses per 2,000 meters of main channel (Table 27, 28 and 29) since it is impossible to know which laterals are open in each modeling area, and for validation purposes. It was assumed that all estimated losses translate into seepage under the premise that evaporation is negligible in channels like those that constitute the irrigation canals which tend to be narrow and deep leaving little superficial area for evaporation to occur and were infiltration rates are much larger and evaporation rates. It was assumed that seepage/recharge from the Patillas-Guamaní irrigation canals would only occur within the main channels which are far more likely to be constantly flowing than its laterals and where the groundwater recharge is equal to the total water loss. Lastly, missing monthly canal losses were set to be the global average of each channel: 910 m^3/d/2,000m for the Patillas canal, 338 m^3/d/2,000m for the Guamaní Este canal and 715 m^3/d/2,000m for the Guamaní Oeste canal.

Table 27. Maximum, minimum and average monthly irrigation water losses through the Patillas canal and its translation to daily losses per 2,000 meters of main channel length assuming an average wetting length of 40,381 meters.[37]

Year	**Maximum (m3/mo)**	**Minimum (m3/mo)**	**Average (m3/mo)**	**Maximum (m3/d/2000m)**	**Minimum (m3/d/2000m)**	**Average (m3/d/2000m)**
1980	1,121,233	423,084	700,103	1,832	670	1,129
1991	701,850	75,267	370,590	1,139	273	703
1992	705,526	170,072	455,447	1,118	269	730
1993	1,776,828	341,649	600,002	2,909	541	968
1994	784,148	204,992	532,698	1,242	336	861
1995	961,831	602,481	749,282	1,524	955	1,209
1996	922,594	120,832	593,601	1,462	191	961
1997	610,388	354,268	484,797	999	561	782
Global	1,776,828	75,267	564,400	2,909	123	910

Table 28. Maximum, minimum and average monthly irrigation water losses through the Guamaní Este canal and its translation to daily losses per 2,000 meters if main channel length assuming an average wetting length of 6,402 meters. [37]

Year	**Maximum (m3/mo)**	**Minimum (m3/mo)**	**Average (m3/mo)**	**Maximum (m3/d/2000m)**	**Minimum (m3/d/2000m)**	**Average (m3/d/2000m)**
1980	123,348	11,101	32,194	1,365	115	338

37 - Guayama Irrigation District (2010)

Table 29. Maximum, minimum and average monthly irrigation water losses through the Guamaní Oeste canal and its translation to daily losses per 2,000 meters of main channel length assuming an average wetting length of 22,474 meters. [37]

Year	Maximum (m^3/mo)	Minimum (m^3/mo)	Average (m^3/mo)	Maximum (m^3/d/2000m)	Minimum (m^3/d/2000m)	Average (m^3/d/2000m)
1980	233,128	48,846	121,765	686	144	352
1984	896,740	325,639	526,799	2,638	927	1,532
1991	497,314	119,117	310,847	1,139	273	703
1992	1,122,121	142,812	549,248	2,486	316	1,229
1993	597,929	102,231	305,855	1,325	234	686
1994	326,564	114,418	221,052	801	254	502
1995	931,055	70,629	226,372	2,063	156	509
1996	252,074	139,618	194,483	559	309	440
1997	502,717	134,129	215,175	1,114	307	484
Global	595,500	133,000	266,000	2,638	144	715

These assumptions were validated based on estimation of seepage from a section of the Patillas irrigation canal. Seepage from canals was estimated according to the differences in water flow given from two USGS stations located in the canals, taking into consideration the water deliveries of the intakes between them. The Canal de Patillas at Intake 113 (USGS 50093110) and the Canal de Patillas at Intake 123 (USGS 50093115) are the gauge stations chosen to estimate the infiltration rate or seepage between them, which is assumed to be representative of the infiltration of the entire Patillas-Guamaní irrigation canals. These 2 stations are about 2,000 meters apart from each other, over the agricultural area in eastern Salinas. Evaluation of flow data of 15 minute interval from these 2 gage stations from the 120 days between 7/19/2011 and 9/19/2011 resulted on an estimated infiltration rate ranging between 250 to 1,950 m^3/d, with an average of 860 m^3/d per 2,000 meters of irrigation canals. This estimate is based on the difference in flow measurements between the 2 stations, when both stations registered flow, during periods when water intake was not considered to occur and under the assumption that evaporation is negligible under such a short period of time (15 minute interval). On the other hand, rewetting infiltration (initial abstraction of water from the canal) was estimated based on difference in flow when only the gage station located at the 113 Intake was reporting flow constantly and the station 123 just started to register flow

(USGS WaterWatch). This resulted in an irrigation canal infiltration between 2,570 and 3,550 m^3/d per 2,000 meters when rewetting.

Studies of seepage estimates from the two reservoirs within the study area are scarce. Kuniansky and Rodríguez (2010) estimated a groundwater recharge rate of 0.3 mm/day for a general area on and in the vicinity of the Melanía reservoir. Considering this to be a reasonable estimate of seepage; which translate into groundwater recharge, 0.3 mm/day was used as the seepage rate from the Patillas and Melanía reservoirs. This value corresponds to a groundwater recharge of 371 m^3/d from the Patillas reservoir and 60 m^3/d from the Melanía reservoir.

Estimates of stream, canal and reservoir seepage for the study area contain a large degree of uncertainty because of the lack of measured data and previous studies in the area.

4.18 Aquifer Budged Model and Sea water - Groundwater Interactions

The developed model does not have the capacity to physically estimate the aquifer interactions with the ocean which are inputs and outputs that are outside of the scope of this study. Nonetheless, the susceptibility of the aquifer to saltwater intrusion and its possibility of occurrence, along with groundwater resurface near the coast and coastal leakage of fresh water was taken into consideration lumped with the estimated changes in aquifer storage. So, changes in aquifer storage (also referred as productive zone) and interactions between the aquifer and the ocean were estimated based on an aquifer water budget which estimates the net recharge to the aquifer based on known factors with sea water interactions plus the changes in aquifer storage as result. Change in aquifer storage and sea-fresh water interactions are the product of the known inputs (percolation) minus the known outputs (pumpage) as shown in Equation 19. Percolation from precipitation, streams, irrigation canals, irrigation practices, over irrigation and dams are assumed to be the known inputs that recharged the aquifer and groundwater pumpage are assumed to be the known outputs or extractions from the aquifer. This is under the premise that the South Coast Aquifer; as must aquifers in the world, tend to be and stay in equilibrium between its inputs and outputs in an annual basis where changes in storage is minimal as found by Ramos-Ginés (1994a), Kuniansky *et al*. (2004) and Kuniansky and Rodríguez (2010).

Net Recharge = Percolation – Pumpage 19

A positive result from Equation 19 was represented as groundwater recharge and/or groundwater leakage to the ocean in the form of resurfaced groundwater as springs near the coast line, within the mangrove and coastal wetlands or in the ocean floor. On the other side, a negative result from Equation 19 means groundwater depletion with the possibility of saltwater intrusion to the aquifer. The groundwater leakage to the sea, to and near mangrove swamps and resurface of groundwater in low parts near the ocean in the Salinas area that occurred during and after the furrow irrigation period is thoroughly documented by Kuniansky and Rodríguez (2010).

4.19 Piezometric Elevations

Piezometric elevation from USGS observation wells obtained from the USGS Groundwater Watch: Puerto Rico Active Water Level Network in the Salinas and Guayama area. They are used as a variable that describes the condition of the water table aquifer as a dynamical system in relation to the estimated net aquifer recharge. Even when the developed model is not capable of estimating differences in piezometric elevation, the estimated net recharge is expected to be able to follow or mimic the fluctuation in piezometric elevations describing the state of the system or at least with the intention to describe enough about the system to determine its possible behavior. Positive net recharge in a monthly basis is expected to reduce or stop the depletion in piezometric elevation or the increase the piezometric elevation in the case of big recharge events. This is translated into an increase in the slope created by piezometric elevations when plotted. On the opposite side, negative net recharge represents piezometric elevation depletion reflected in a decrease in slope when piezometric elevations are plotted.

Tables 30 and 31 present the 10 observation wells, with their surface elevation and data period from where monthly average piezometric elevations were used for evaluation of groundwater recharge in the Salinas area.

Table 30. Observation wells, surface elevation and data period from where monthly average piezometric elevations was used as state variable for evaluation of groundwater recharge in the Salinas area.[38]

Observation Well	Surface Elevation (m)	Data Period
JBNERR EAST 1 - USGS 175711066143600	1.5	11/2005 through 10/2010
JBNERR EAST 2 - USGS 175711066143601	1.5	11/2005 through 10/2010
JBNERR WEST 1 – USGS 175721066151400	2.1	11/2005 through 12/2010
JBNERR WEST 2 – USGS 175721066151401	2.1	11/2005 through 12/2010
A RASA - USGS 175833066145800	27.4	7/1992 through 12/2010
D RASA - USGS 175910066155500	22.0	2/1997 through 12/2010
AGUIRRE - USGS 175947066130601	61.2	4/1988 through 10/2010
COQUI - USGS 175809066133100	4.9	3/1997 through 9/2009

Table 31. Observation wells, surface elevation and data period from where monthly average piezometric elevations was used as state variable for evaluation of groundwater recharge in the Guayama area. [38]

Observation Well	Surface Elevation (m)	Data Period
PHILPET 13 - USGS 175719066085500	30.2	1/1992 through 10/2010
JUANA 5 WELL - USGS 175858066100200	39.0	4/1982 through 10/2010

4.20 Sensitivity Analysis

When developing a model, the response of the model should closely mimic the response of the real world system being modeled (Anderson and Burt, 1985). When modeling, it is extremely important to completely understand the way the model responds to the different inputs or parameters used in the model (McCuen, 1973). Sensitivity analysis is a modeling tool that has been used in previous water budget studies to understand the importance of variables and the effects of errors on inputs and on

38 - USGS Groundwater Watch: Puerto Rico Active Water Level Network

computed outputs. Through a sensitivity analysis the modeler is able to identify the most important input variables of the model, the effect of input errors on the predicted output, and the physical hydrologic variables that are most likely related to fit model parameters, among others (McCuen, 1973).

A sensitivity analysis was carried out to determine the relative sensitivity of the predictions to the different parameters of the model for the Salinas modeling area. Local sensitivity measures were conducted following the recommendations from Saltelli *et al.* (2004) and Rivera-Santos (1988). Ten percent variation on the input parameter was used to estimate its local sensitivity based on the effect that this variation caused in the estimated annual net recharge for each year, data which was used to create the sensitivity matrix *A*. The sensitivity matrix *A* is an *n* x *p* matrix where *n* is the size of the datum in years (31 years) and *p* is the number of parameters used for the sensitivity analysis (30 parameters) which are listed in Table 32. Then a normalized *A* matrix is calculated from

$$a_{ij} = \frac{P}{y}\frac{\partial Y_{ij}}{\partial P_j} \quad \text{where } i \text{ varies from 1 to } n \text{ and } j \text{ from 1 to } p \qquad 20$$

a is the term in row *i* and column *j*

Y is the initial parameter

P is the initial net recharge

∂Y_{ij} is the difference in net recharge for *i* and parameter *j*

∂P_j is the difference in initial parameter and its varied value (10 percent)

Been Salinas the most critical area in terms of recharge minus extraction (net groundwater recharge) it was the modeling area selected for sensitivity analysis for the entire study period. The objective of the performed sensitivity analysis is to identify which parameters are important in determining net groundwater recharge when using this model. Parameters that in average caused more than 1 percent change in the result were selected as the most sensitive.

Table 32. Parameters used for sensitivity analysis.

Parameter	**Description**
Kc I	Evapotranspiration coefficient for irrigated areas
Kc NI	Evapotranspiration coefficient for non irrigated areas
Eff. R I	Effective root depth for irrigated areas
Eff. R NI	Effective root depth for non irrigated areas
AD I	Allowed water depletion for irrigated areas
AD NI	Allowed water depletion for non irrigated areas
θ	Weighed average soil water content
Lc	Weighed average soil depth
AMC 2 I	Antecedent soil moisture content, conditions II, for irrigated areas
AMC 1 I	Antecedent soil moisture content, conditions I, for irrigated areas
AMC 3 I	Antecedent soil moisture content, conditions III, for irrigated areas
AMC 2 NI	Antecedent soil moisture content, conditions II, for non irrigated areas
AMC 1 NI	Antecedent soil moisture content, conditions I, for non irrigated areas
AMC 3 NI	Antecedent soil moisture content, conditions III, for non irrigated areas
W area	Watershed area
I area	Irrigated area
Area out A	Area out of the alluvium
I eff	Irrigation efficiency
I perc	Percolation from irrigation
Majada	Streambed seepage from Rio Majada
Lapa	Streambed seepage from Rio Lapa
Nigua	Streambed seepage from Rio Nigua
Aguas Verdes	Streambed seepage from Quebrada Aguas Verdes
Self	Groundwater pumpage for self supply
PRASA	Groundwater pumpage for PRASA
PREPA	Groundwater pumpage for PREPA
Pw. req	Groundwater pumpage for Irrigation
Canal P	Seepage from Patillas Canal
Canal G	Seepage from Guamaní Canal
Iad	Surface water imports

5. Results

5.1 Weather Data

Recharge within the study area has been typically linked to annual precipitation as previously done by Giusti (1971), McClymonds and Díaz (1972), Ramos-Ginés (1994a) and Kuniansky *et al.* (2004). Nonetheless, it is believed that recharge is as dependant on annual precipitation distribution as it is for annual total precipitation. This speculation is based on a simple analysis of recharge estimates and estimated precipitation-recharge. Further research in the subject is recommended.

Annual precipitation for the four weather stations within the study area is presented in Figure 50 and average annual precipitation for each weather station is presented in Figure 51. The average annual precipitation rate for each decade within the study period is presented in Table 33. In general, the 1990s was the driest decade where annual precipitation considerably decreased from the 1980s to the 1990s in the Aguirre and Jájome Alto area but slight increased in the Guayama and Patillas area. More significantly, in all four weather stations the average 10 year period of precipitation increased considerably from the 1990s to the 2000s, been the 2000s the wettest decade of the three decades that include the current study.

A histogram of daily precipitation in the study area for January 1980 through December 2010 is presented in Figure 52. There were only 30 days with 24-hour precipitation greater than 104 mm during this period. The highest 24-hour precipitation during the study period was 508 mm for the Patillas and Guayama weather stations which was registered on September 22 of 2008 from a severe storm (that eventually developed into hurricane Kyle). Finally, 512 mm in the Jájome Alto weather station on January 6, 1992 was registered from a severe storm that caused a state of emergency, and 312 mm on Aguirre on October 7, 1985 was registered when what was eventually called tropical storm Isabel moved directly south of Salinas.

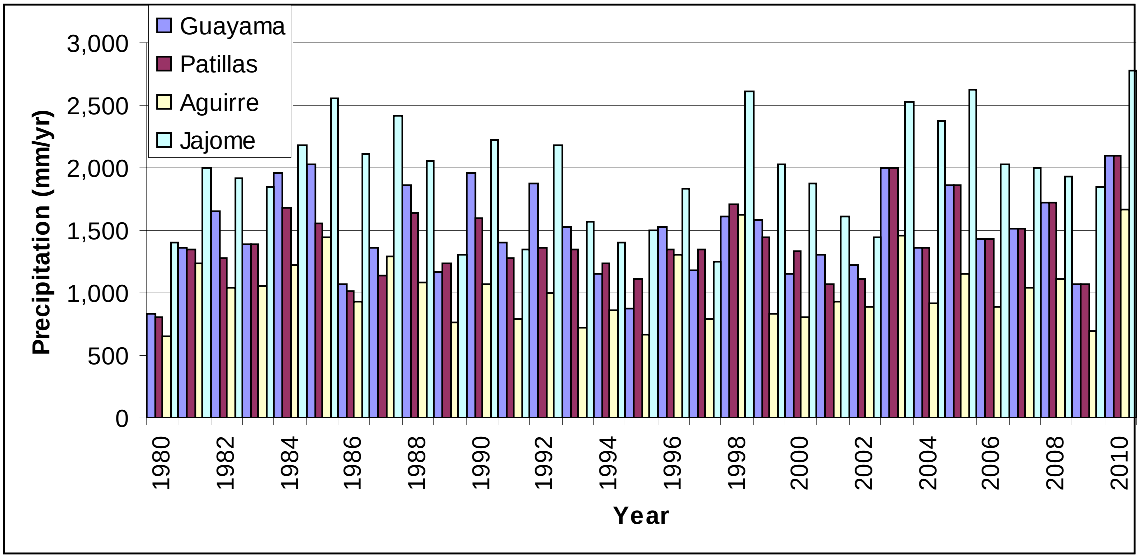

Figure 50. Annual precipitation distribution for each weather station.

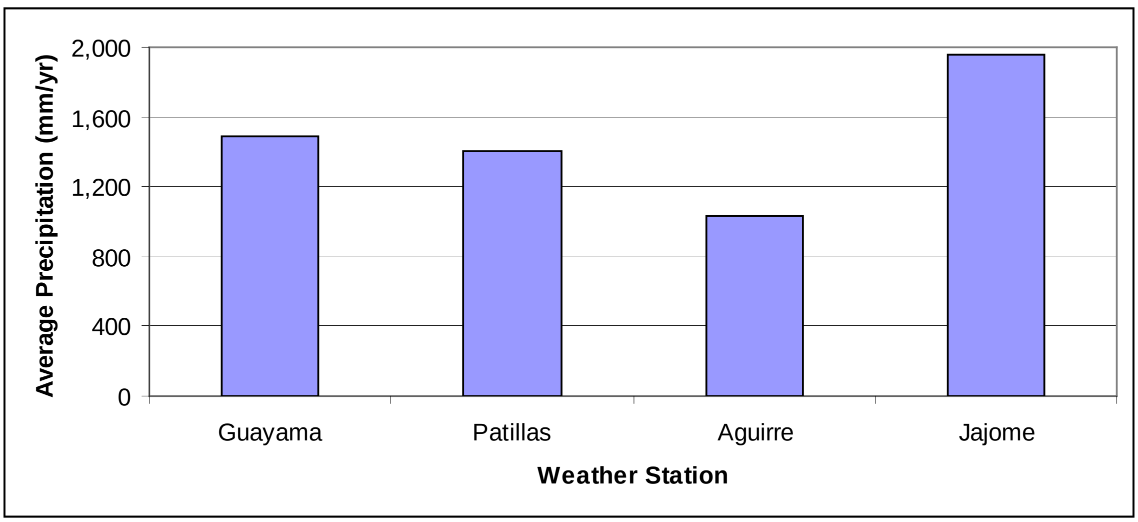

Figure 51. Average annual precipitation for each weather station used.

Table 33. Average annual precipitation rate for each weather station for each decade of the study period.

Period	Guayama	Patillas	Aguirre	Jájome Alto
1980s	1469	1309	1072	1980
1990s	1470	1377	966	1793
2000s	1522	1506	1050	2096
1980-2010	1488	1401	1030	1961

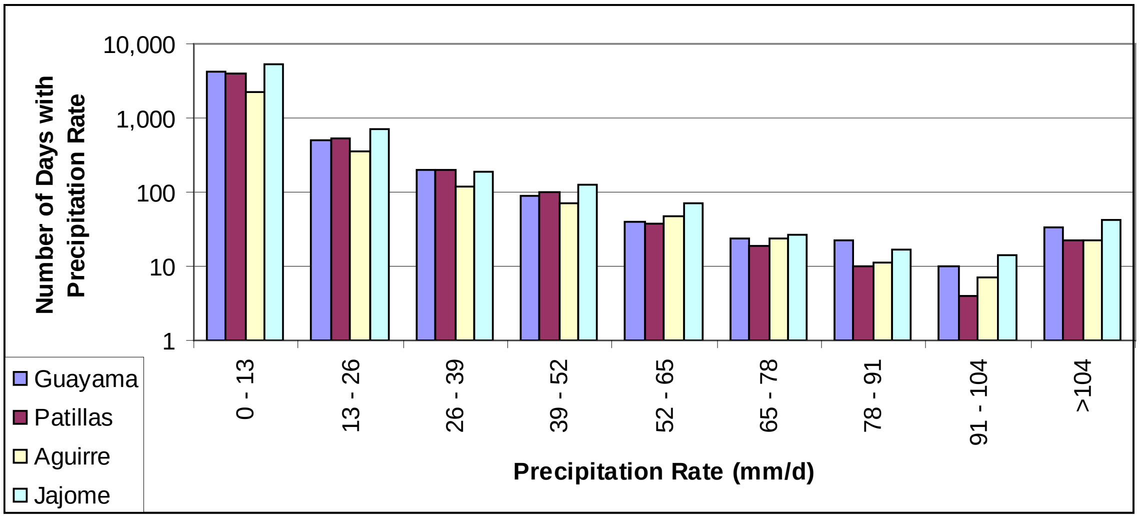

Figure 52. Log scaled histogram of 24-hour precipitation for the weather stations.

ET_0 fluctuated from day to day, as indicated in Figure 53. As expected in tropical places, the monthly trend in ET_0 during a given year is trapezoidal-shaped from February 1 to December 1, increasing in the spring, flattening during the summer, decreasing in the autumn and flattening again in the winter (Figure 53). However, the annual total ET_0 show clear changes between the first and second part of the study period as shown in Figure 54. There is a decrease in the average ET_0 during the year 1994 and then again in the year 1999. This is the direct result of an annual decrease ET_0 estimates for these weather stations. ET_0 clearly decreased during the year 1994 for the Guayama weather station and during the year 1999 for the Aguirre weather station as shown in Figure 55. A quick overview of the reported daily maximum and minimum temperatures (Figures 56 and 57) show a change in the difference daily temperature (Max – Min) and a change in daily variability between this two. It is considered that this may be the result of two possible factors:

1. A change in the time of the day where maximum and minimum temperature were measured.
2. A change in the instruments itself.

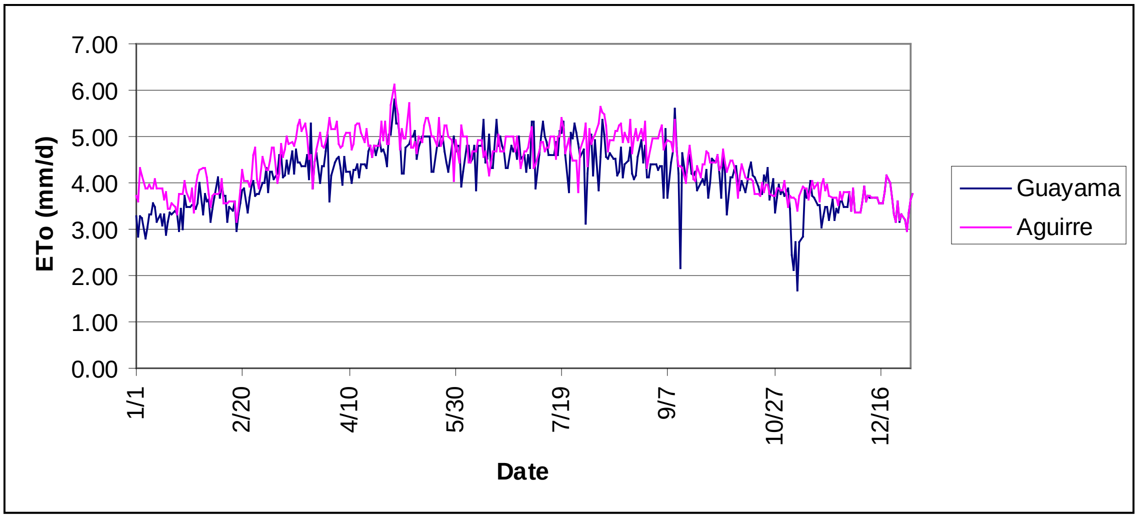

Figure 53. Daily reference evapotranspiration (ET_0) for the year 1984 based on data from the Guayama and Aguirre weather stations.

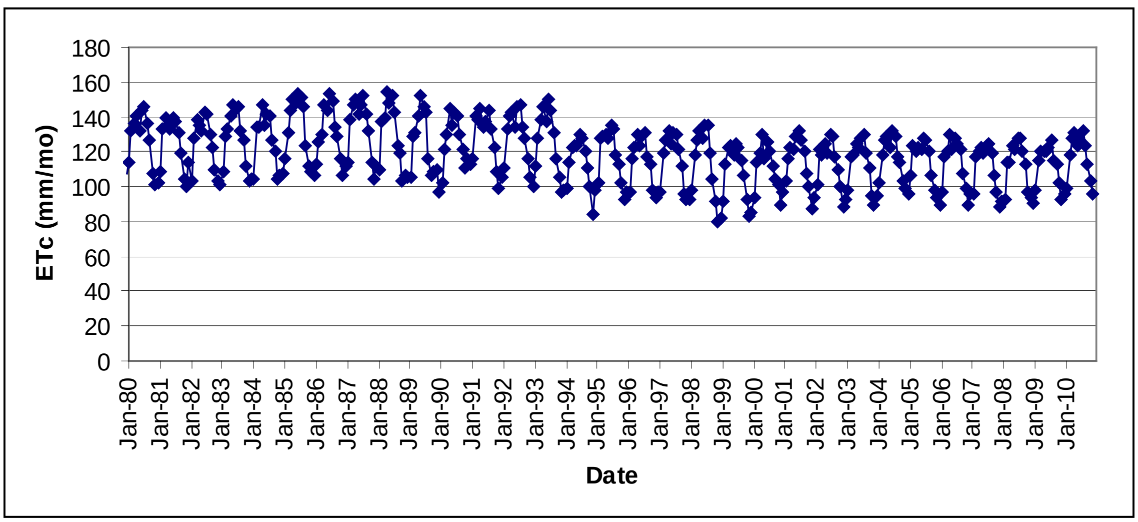

Figure 54. Estimated average monthly actual evapotranspiration (ETc).

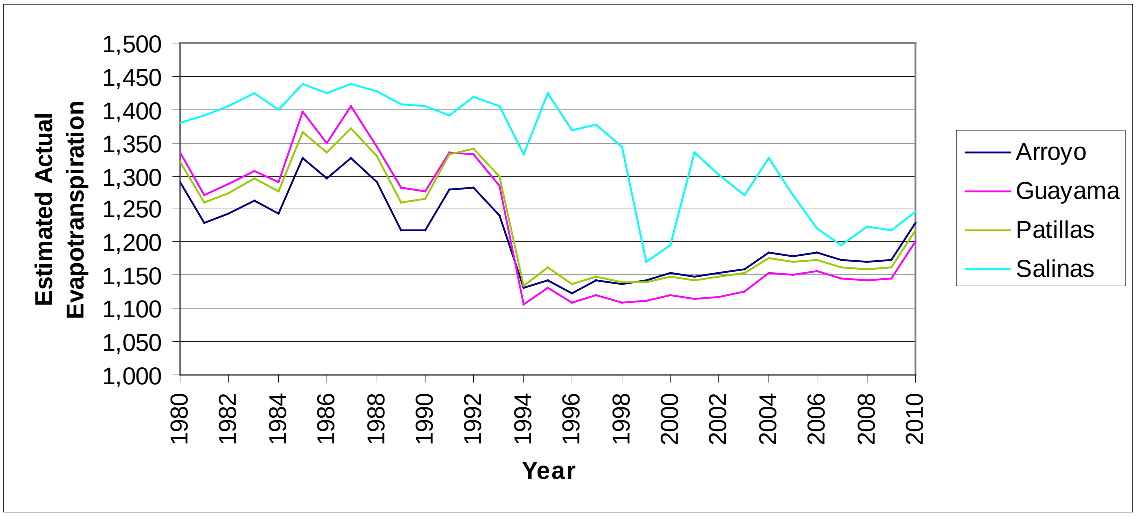

Figure 55. Estimated annual actual evapotranspiration (ETc) for each modeling area.

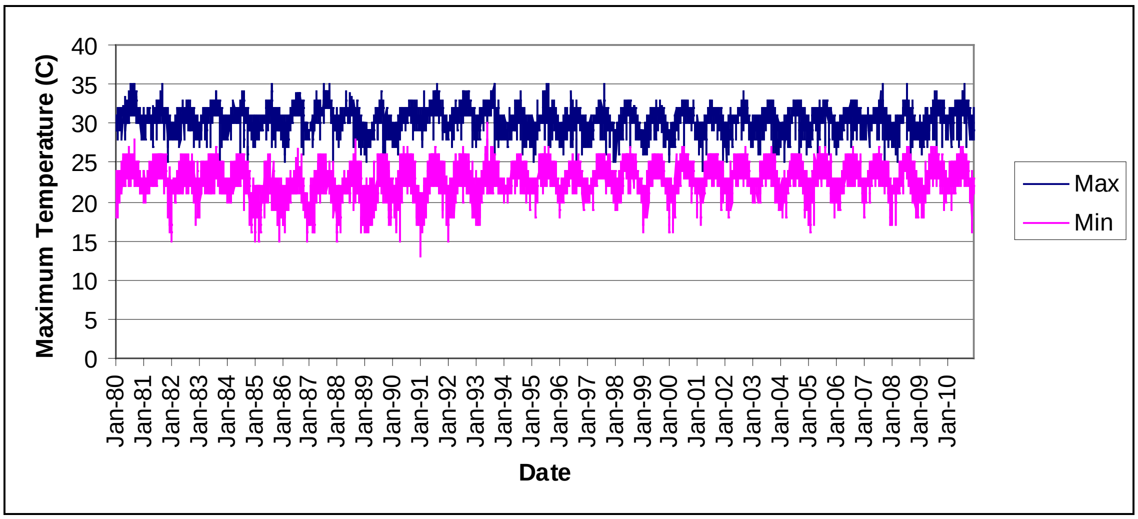

Figure 56. Daily maximum and minimum temperature as reported for the Guayama weather station (CLIMOD).

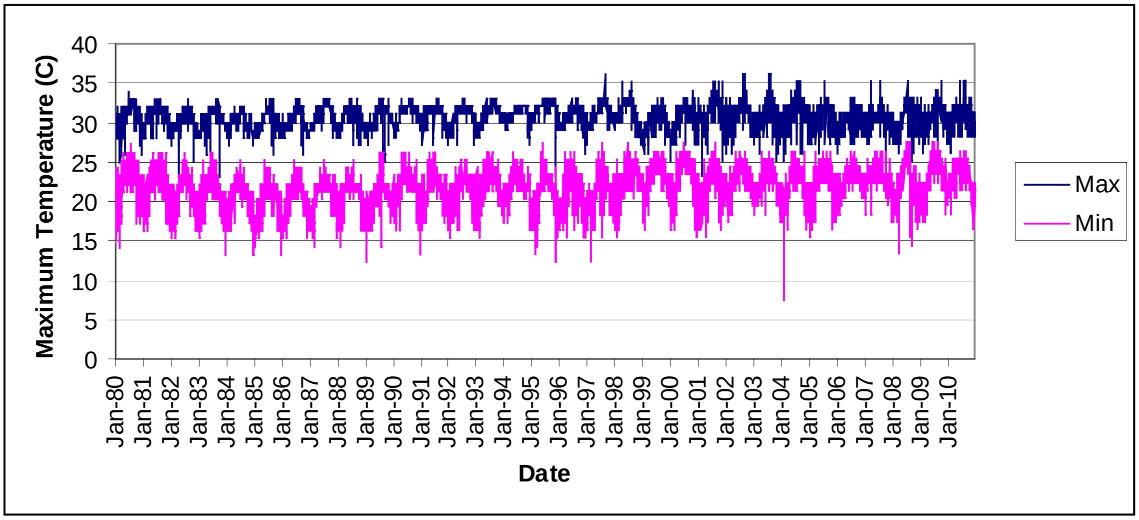

Figure 57. Daily maximum and minimum temperature as reported for the Aguirre weather station (CLIMOD).

5.2 Estimated Annual Groundwater Recharge

Annual recharge from precipitation and irrigation was estimated as the infiltration from precipitation and/or irrigation that exceeds the soil moisture capacity (also called percolation) as described from the Materials and Methods section of the current study. In that section, infiltration from precipitation was assumed to be precipitation minus runoff under the premises that interception and ponding is small enough to be evapotranspired within 24 hours. Annual precipitation and evapotranspiration have been already presented, while estimated annual runoff is shown in Figure 58 for each modeling area. Estimated runoff; by far, represents the factor with the highest uncertainty in the precipitation-infiltration relationship estimates. Percolation or recharge from irrigation was estimated based on irrigation efficiency and over irrigation as explained in the Materials and Method 4.6 section.

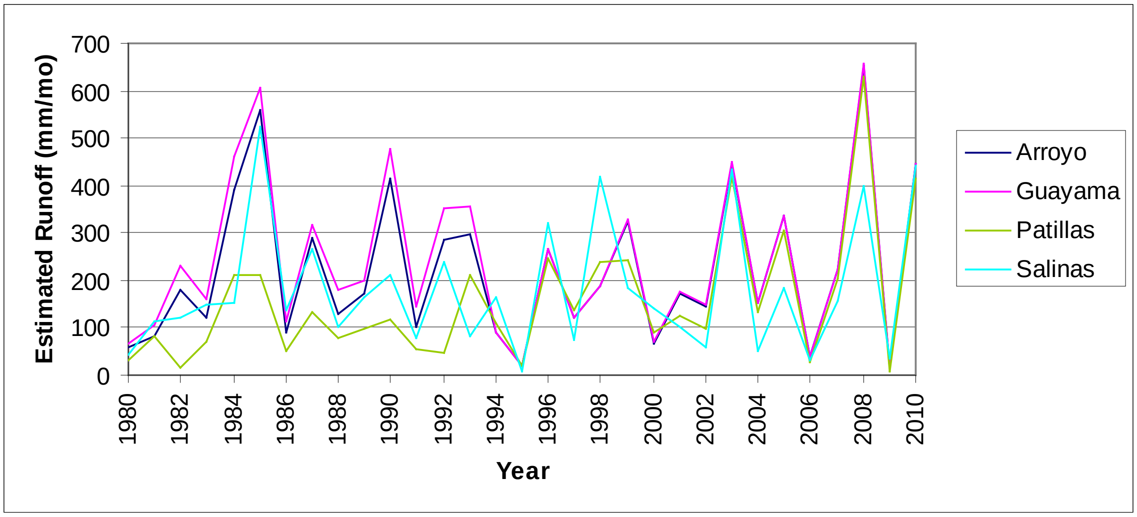

Figure 58. Estimated annual runoff based on the SCS CN method per modeling area.

Percolation from precipitation and irrigation that serves as recharge to the aquifer in each modeling area is presented in Figures 59 through 62. Logically, the years with more annual precipitation produced more percolation than the years with less precipitation. In general, the years 1980 and 86, 1994 and 95, and 2002 and 09 were the more critical years in terms of recharge from precipitation water and they are characterized as dry years. The years with the higher precipitation recharge are generally associated with big rain storms, tropical storms and/or hurricanes, like is the case for the years 1985, 1988 and 1998 when tropical storm Isabel and hurricanes Chris and Georges respectively brought extremely high precipitation in a relatively short period of time. On the other hand, years like 1984 and 2010 produced high percolation even with no big precipitation events being recorded because they were wet years that counted with very high cumulative precipitation distributed year around.

Percolation from irrigation gradually decreased from the early 1980s to the mid 2000s as irrigation efficiency gradually increased during this period as it was shown in Table 15. The most significant changes in irrigation water recharge occurred in the Guayama and Salinas modeling areas where during the last three decades an aggressive change from furrow to drip and sprinkler irrigation occurred in comparison to the Arroyo and Patillas modeling areas. Recharge from irrigation water in the 2000s was mostly negligible in the Guayama area and low in the Arroyo, Patillas and Salinas modeling areas when comparing it to the early 1980s.

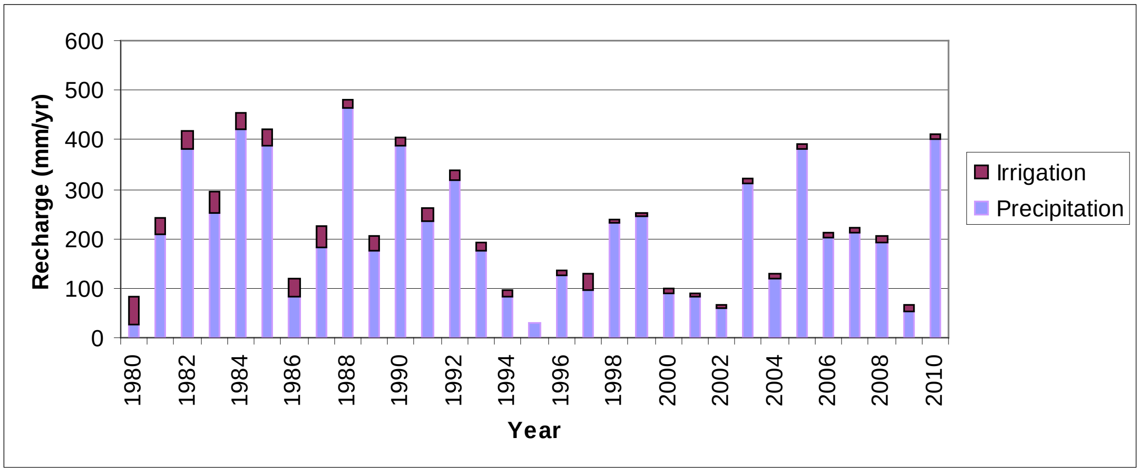

Figure 59. Estimated annual percolation that serve as recharge from precipitation and irrigation for Arroyo modeling area.

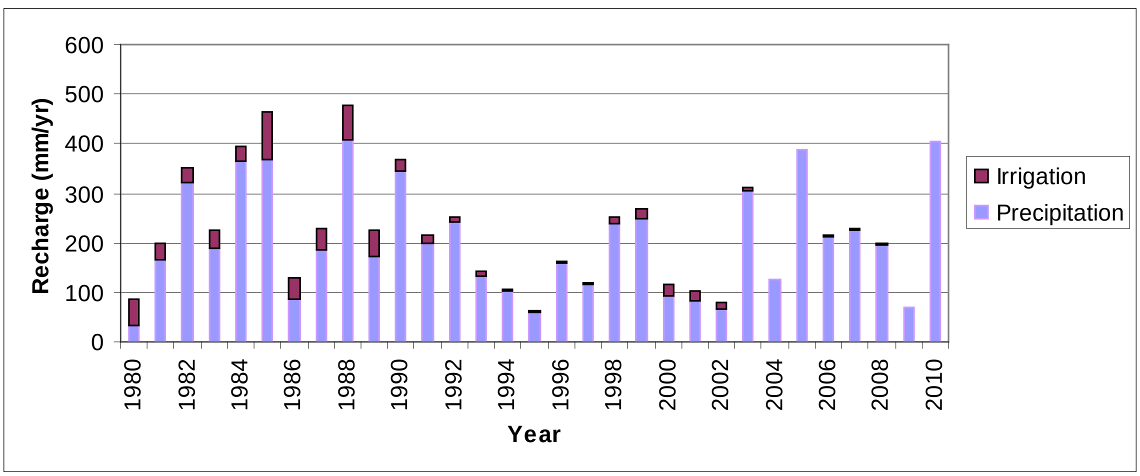

Figure 60. Estimated annual percolation that serve as recharge from precipitation and irrigation for Guayama modeling area.

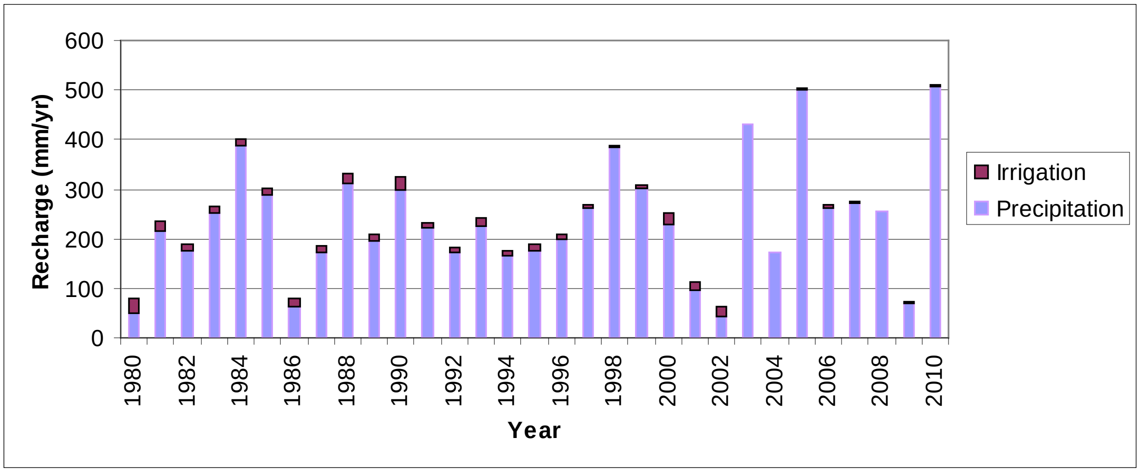

Figure 61. Estimated annual percolation that serve as recharge from precipitation and irrigation for Patillas modeling area.

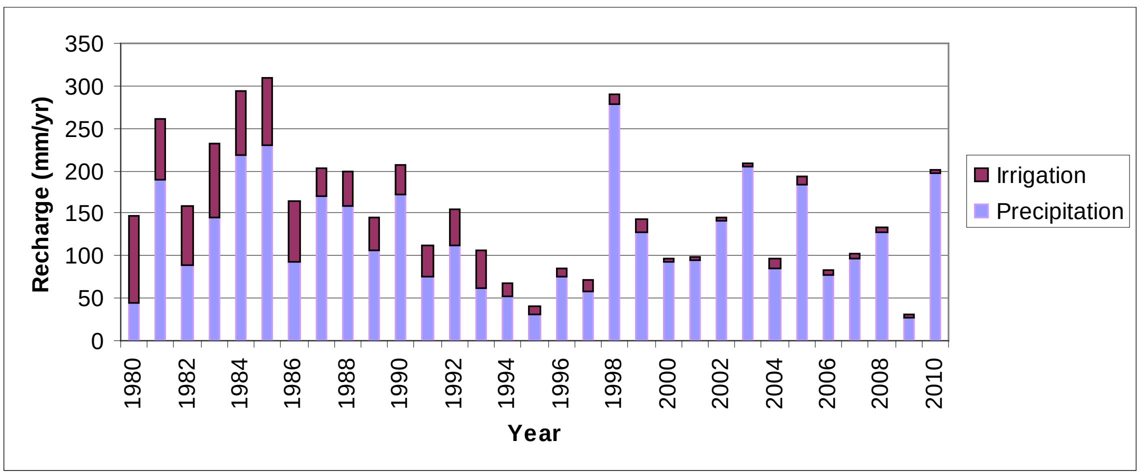

Figure 62. Estimated annual percolation that serve as recharge from precipitation and irrigation for Salinas modeling area.

A general groundwater recharge approximation based on annual precipitation for dry, average and wet years was done following the examples from Giusti (1971), McClymonds and Díaz (1972), Ramos-Ginés (1994a) and Kuniansky *et al.* (2004). Dry, average and wet years are defined based on the average and standard deviation of the data for the 31 year period for each modeling area. Dry years were considered those years which registered precipitation is smaller than one standard deviation of the data, while wet years are those years that registered precipitation is higher than one standard deviation and average years were those which registered precipitation is within one standard deviation from the average precipitation of the total period of the current study.

Table 34 presents the precipitation ranges for dry, average and wet years for each modeling area.

Table 34. Dry, average and wet years for the 31 year study period in mm/yr.

Area	Dry	Average	Wet
Arroyo	<1140	1140 to 1850	>1850
Guayama	<1140	1140 to 1850	>1850
Patillas	<1110	1110 to 1700	>1700
Salinas	<760	760 to 1310	>1310

Tables 35 and 36 presents the estimated average percolation from precipitation water for the two irrigation periods; 1980 through 1993 during the furrow irrigation period and 1994 through 2010 during the sprinkler and drip irrigation period. Average percolation from precipitation that serves as groundwater recharge is considerably higher during the furrow irrigation period because during this period agricultural soils were at or near field capacity (maximum plant available soil moisture) must of the time as direct consequence of furrow irrigation practices. This caused the soil moisture to turn gravitational soil water when precipitation events took place far more often than in drip and sprinkler irrigation fields. It's widely known that percolation from precipitation events is greater in irrigation fields than in naturally occurring areas. In a recent study Arnold (2011) using field plots in the Weld County of Colorado, found that for flood irrigation about 29 to 39 percent of irrigation water plus precipitation percolated during the years 2008 and 09 and that in sprinkler irrigated fields about 4 to 11 percent of irrigation water plus precipitation during the study period. Also, Christen *et al.* (2006), in a study performed in Australia in vegetable fields, found that 2 and 26 percent of precipitation percolated as direct result of drip and furrow irrigation respectively.

In the current Salinas to Patillas study area it was found that between 10 and 40 percent of total precipitation recharge comes as direct result of irrigation practices or, in other words, that there is a considerable increment in overall recharge from precipitation to the aquifer because of irrigation practices, especially from furrow irrigation. In irrigated fields' soil moisture is keep high to satisfy the plant water requirement, this causes the soil to reach field capacity and saturation faster and more often than non irrigated fields. Deep percolation occurs each time the soil moisture surpasses saturation.

Table 35. Estimated average annual percolation from precipitation, 1980 through 1993 per modeling area in percentage.

Area of Interest	**Dry**	**Average**	**Wet**
Arroyo	6	16	19
Guayama	6	16	19
Patillas	6	17	22
Salinas	8	13	16

Table 36. Estimated average annual percolation from precipitation, 1994 through 2010 per modeling area in percentage.

Area of Interest	**Dry**	**Average**	**Wet**
Arroyo	4	9	16
Guayama	4	9	16
Patillas	7	17	22
Salinas	4	11	14

Although none of them seriously considered the possible increase in precipitation percolation as direct result for irrigation practices in agricultural areas, Giusti (1971) and Ramos-Ginés (1994a) in the vicinity of Coamo-Juana Díaz area estimated a 10 % recharge to the aquifer from precipitation for average years. McClymonds and Díaz (1972) estimated that effectively in the central section of the South Coast Aquifer about 10% of precipitation recharges the aquifer in average years, and that more than 10% serve as recharge in wet years and less in dry years. In the same way, Kuniansky *et al.* (2004) in their study performed in the Santa Isabel area (which is directly west of the Salinas modeling area) estimated that 4 percent of precipitation recharged the aquifer during dry years, 8 percent during average years and 12 percent during wet years for their study period between 1987 and 2001. For comparison and validation purposes, the water budget model developed for the Salinas area in the current study was adapted to the precipitation conditions and period established by Kuniansky *et al.* (2004), shown in Table 37, where results are fairly similar considering the assumptions taken for each model and the similarity of the hydrological conditions between both areas. It is considered that the difference in percolation from precipitation that recharges the aquifer strives in the fact that the water budget model developed here, takes into consideration the soil moisture prior to each precipitation event when estimating the precipitation water percolation and aquifer recharge. Since in irrigated areas soil moisture tends to be higher than in non irrigated areas, percolation from precipitation in irrigated areas also tends to be higher as Arnold (2011) and Christen *et al.* (2006) have found.

Table 37. Comparison between estimates percentage (%) of average percolation from precipitations from 1987 through 2001 where dry years are when precipitation is smaller than 760 mm and wet years is when is higher than 1020 mm.

Source	**Dry**	**Average**	**Wet**
Kuniansky *et al.* (2004) in Santa Isabel	4	8	12
Estimated for Salinas	7	11	13

In terms of groundwater recharge from irrigation practices, Quiñones-Aponte *et al.* (1997) stated that about 30 percent of total applied irrigation in the Salinas to Patillas area recharges the aquifer, and Bennett (1976) and Kuniansky et al. (2004) estimated that as much as 30 percent of the water applied through furrow irrigation recharges the aquifer in the vicinity of Santa Isabel. Based on water deliveries data by PREPA and irrigation efficiency estimates, it is theorized that in furrow irrigation fields about 20 percent of the irrigation water applied actually recharge the aquifer, where other 10 to 40 percent of recharge attributed by other researchers is actually recharge from precipitation in irrigated fields. This is precipitation that would not have percolated if no irrigation was present. In the same way, it is theorized that none of the water imported for drip irrigation percolates and that in sprinkler irrigated fields only about 5% of the imported water percolates, where all other percolation come from the interaction with precipitation.

Table 38. Estimated average annual percolation from irrigation, for irrigation periods between 1980 through 1993 per modeling area in mm/yr.

Area	**1980 – 86**	**1987 - 93**
Arroyo	38	25
Guayama	47	38
Patillas	16	15
Salinas	79	39

The estimated average percolation from irrigation application for each irrigation period per modeling area are presented in Tables 38 and 39 where a substantial decrease in irrigation water percolation that recharges the aquifer is seen from the 1980 to 1986 and the 2005 to 2010 periods.

Table 39. Estimated average annual percolation from irrigation, for irrigation periods between 1994 through 2010 per modeling area in mm/yr.

Area	**1994 - 99**	**2000 - 04**	**2005 - 10**
Arroyo	11	8	11
Guayama	5	16	2
Patillas	9	12	3
Salinas	13	5	5

Following statements from McClymonds and Díaz (1972), Ramos-Ginés (1994b and 1994c), Quiñones-Aponte *et al.* (1997) and Kuniansky and Rodríguez (2010), recharge to the South Coast aquifer from streams was estimated to be the same as the estimated base flow for the streams within the study area under the premise that all base flow infiltrates through the alluvium and only event elated flow is discharged to the ocean. Table 40 and Figures 63 through 66 present the estimated percolation that serve as recharge to the aquifer (which was estimated to be the same as base flow) for each modeling area and the watersheds that drain through it. It is estimated that streams in the Salinas modeling area (Figure 66 and Table 40) brings the most significant contribution to the aquifer providing a higher annual rate of recharge while the Patillas modeling area experiences the lowest contribution to aquifer recharge from streams due to the blockage that the Patillas Dam creates to the two principal streams, Río Grande de Patillas and Río Marín. Validation of this estimates have been already assessed in the Base Flow 4.17 section of the Materials and Methods chapter.

Table 40. Estimated average annual percolation from streams, per modeling area per decade in mm/yr.

Area	**1980 - 89**	**1990 - 99**	**2000 - 10**
Arroyo	28	32	40
Guayama	30	34	38
Patillas	18	21	26
Salinas	135	129	161
Total	211	216	265

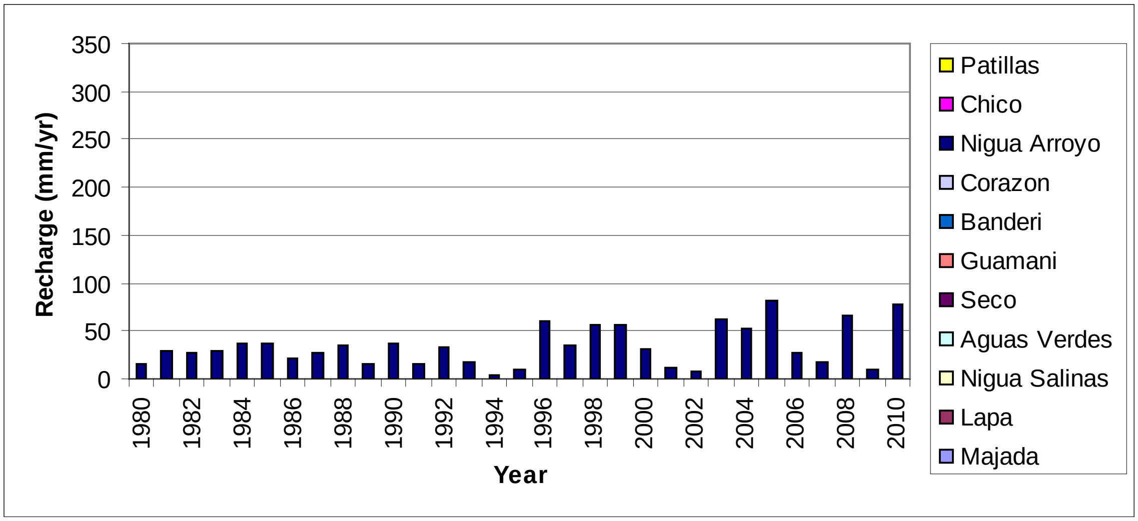

Figure 63. Estimated annual percolation that serve as recharge from streams base flow for Arroyo modeling area (Río Nigua de Arroyo watershed).

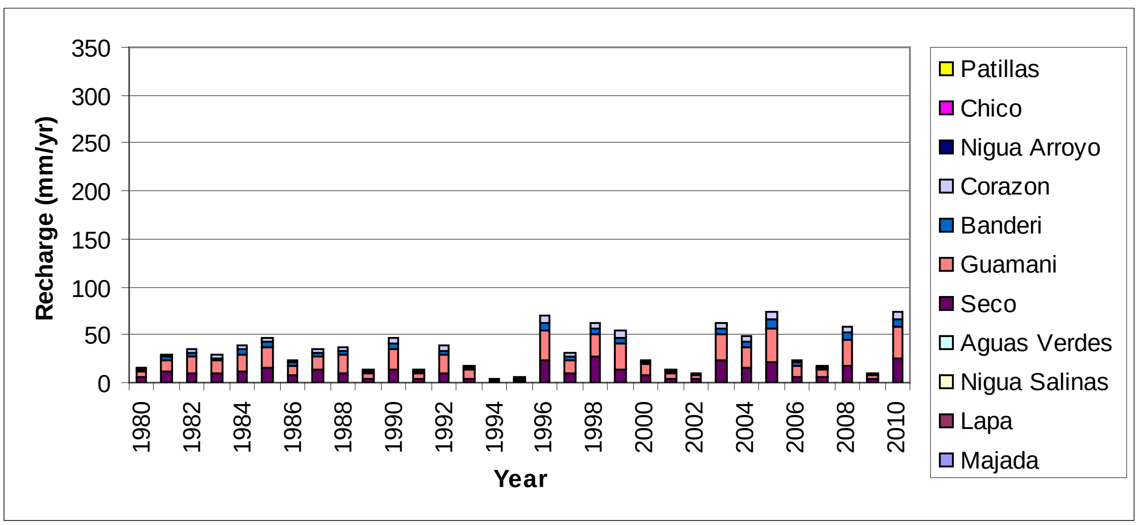

Figure 64. Estimated annual percolation that serve as recharge from streams base flow for Guayama modeling area (Río Seco, Río Guamaní, Quebrada Branderi, Quebrada Corazón watersheds).

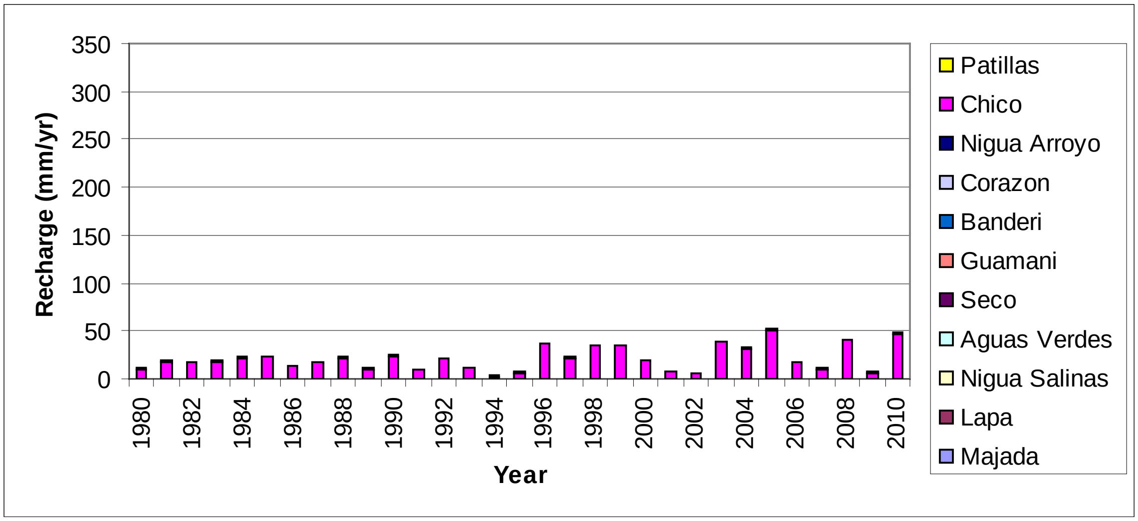

Figure 65. Estimated annual percolation that serve as recharge from streams base flow for Patillas modeling area (Río Chico, Río Grande de Patillas and Río Marín watersheds where the latter 2 are dammed).

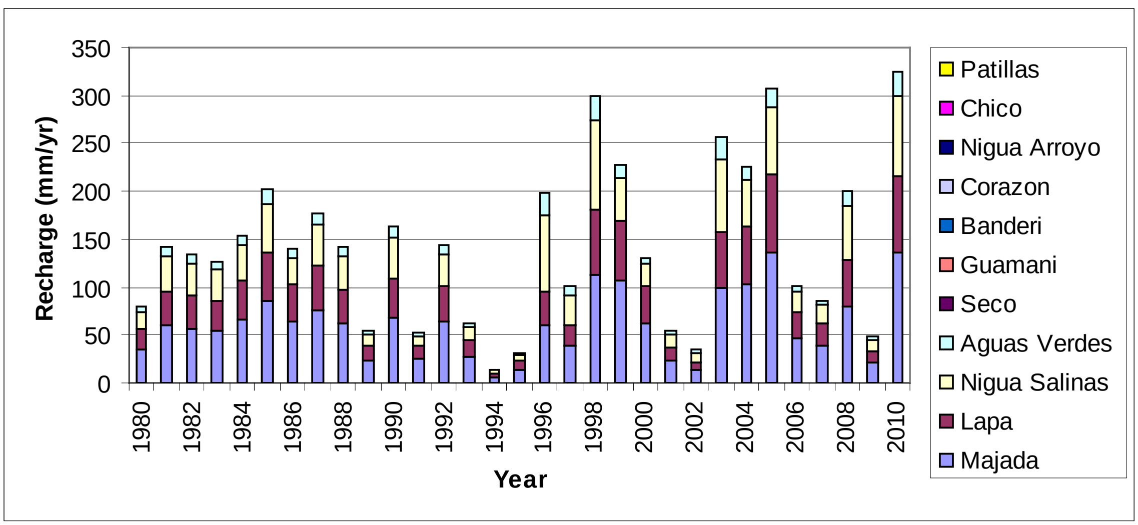

Figure 66. Estimated annual percolation that serve as recharge from streams base flow for Salinas modeling area (Río Majada, Río Lapa and Río Nigua de Salinas).

Estimated groundwater recharge from irrigation canals; although significant when compared to recharge from streams, is small when compared to recharge from precipitation. Aquifer recharge from the canals is greater in the Guayama and Salinas area where there is more lineal canal extension because both, the Patillas and Guamaní irrigation canals run through these modeling areas while only the Patillas canal runs through the Arroyo and Patillas modeling areas. Table 41 presents the average annual aquifer recharge from irrigation canals estimated for each modeling area. Even when it might seem small, it is believed that the irrigation canals are a very important source of groundwater recharge because of its continuous and safe input to groundwater. While recharge from irrigation, precipitation and streams varies from year to year, recharge from the irrigation canals have been a constant factor which can be a significant source of groundwater recharge for years of extreme drought such as the years 1980 and 1995.

Table 41. Estimated annual recharge from irrigation canals per modeling area.[39]

Modeling Area	Recharge from Canal (mm/yr)
Arroyo	22
Guayama	36
Patillas	11
Salinas	38

Estimated groundwater recharge from the two reservoirs (Table 42) within the study area is insignificant when compared to any of the other recharge inputs. Actual recharge from reservoirs may vary from these estimates and further research on the subject is recommended.

Table 42. Estimated annual recharge from reservoirs per modeling area.

Modeling Area	Recharge from Reservoir (mm/yr)
Guayama; Melanía Reservoir	0.2 (negligible)
Patillas; Patillas Reservoir	2

Figures 67 through 70 combines and summarizes the total percolation water that is believed to serves as aquifer recharge. The general order of importance for groundwater recharge inputs were estimated as precipitation, streams, canals, irrigation and dams. Although this is true for Guayama, Arroyo and Patillas, interestingly it is not for Salinas. While in the Arroyo, Guayama and Patillas modeling areas, precipitation represents the greater input for groundwater recharge; in the Salinas area is the stream percolation the more important input where in few cases canal recharge was more important than precipitation. Table 43 presents the estimated average of total recharge for each modeling area for the 31 year study period. The relative spatial and temporal importance of recharge input is discussed later on.

39 - For the entire study period.

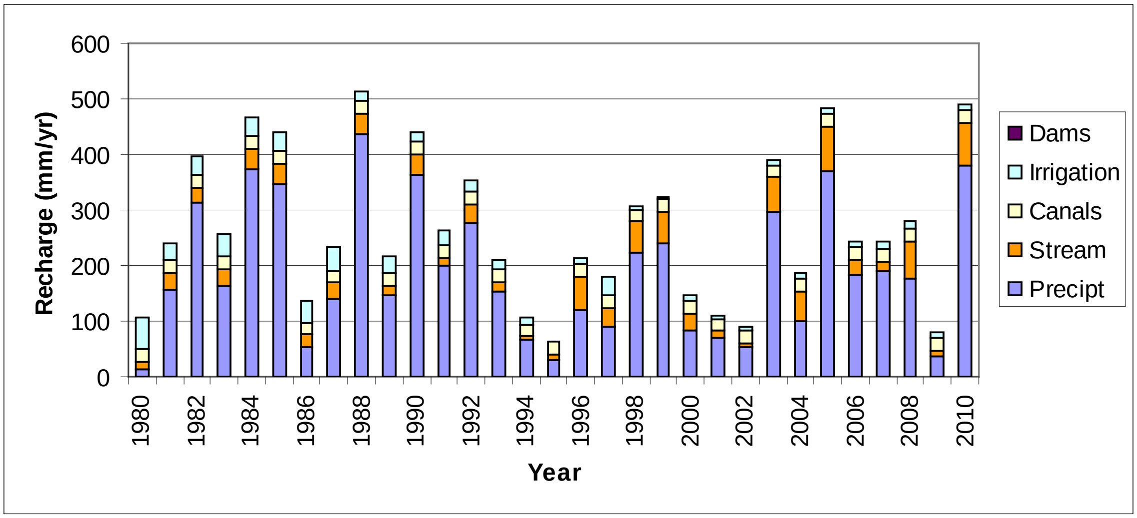

Figure 67. Estimated annual percolation that recharges de aquifer in Arroyo modeling area.

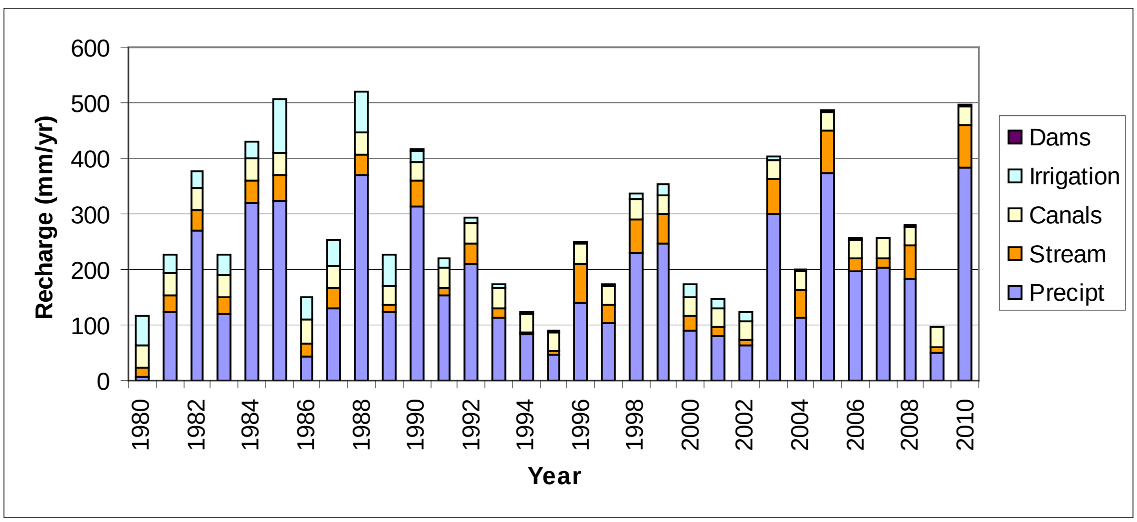

Figure 68. Estimated annual percolation that recharges de aquifer in Guayama modeling area.

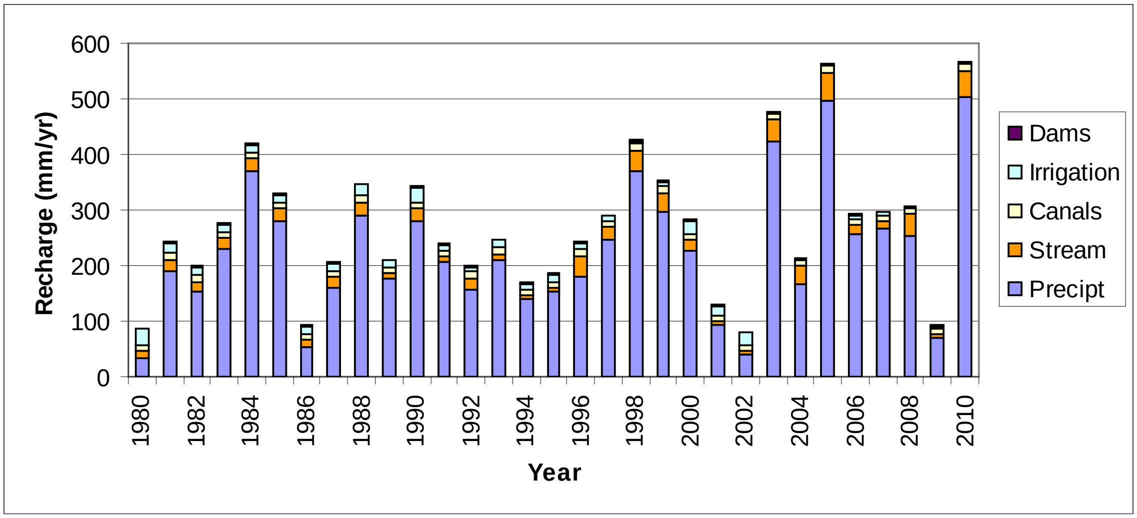

Figure 69. Estimated annual percolation that recharges de aquifer in Patillas modeling area.

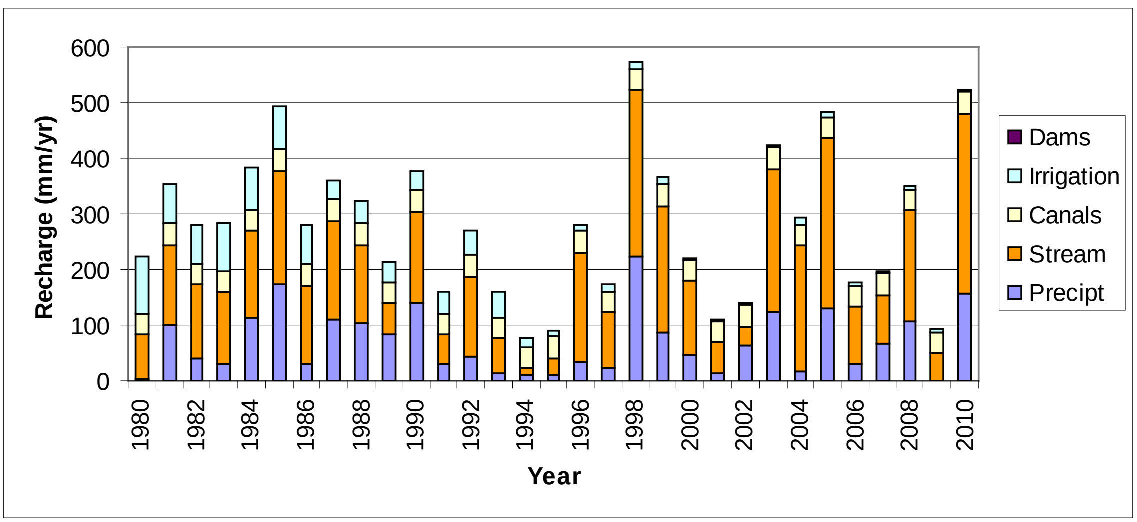

Figure 70. Estimated annual percolation that recharges de aquifer in Salinas modeling area.

Table 43: Estimated average annual total percolation per modeling area in mm/yr.

Area	Recharge
Arroyo	289
Guayama	296
Patillas	284
Salinas	335

5.3 Estimated Annual Groundwater Pumpage

The estimated annual groundwater pumpage used for estimating the net groundwater recharge is presented in Figures 71 to 74 and average annual groundwater pumpage for the two irrigation periods are presented in Table 44. Self served, PRASA, PREPA, industrial and irrigation pumpage was obtained and/or estimated as previously mentioned and represent the tangible outputs from the aquifer. As can be appreciated from Figure 74 and Table 44, groundwater pumpage from PRASA and for irrigation in the Salinas modeling area are far greater and constant than those from the other three modeling areas which; as it will be discussed in the next section, has create great stress and possibly caused saltwater intrusion into the South Coast Aquifer in the Salinas area.

All four modeling areas experienced a reduction in groundwater pumpage pass the sugarcane production due to the reduction in irrigation water requirement and in irrigated area. The greatest reduction in average groundwater pumpage between the prior and after sugarcane production was experienced by Arroyo (49 %) and Guayama experienced the least changes (11 %). Reduction in groundwater pumpage in Patillas and Salinas was estimated to be 27 and 14 percent in average, respectively.

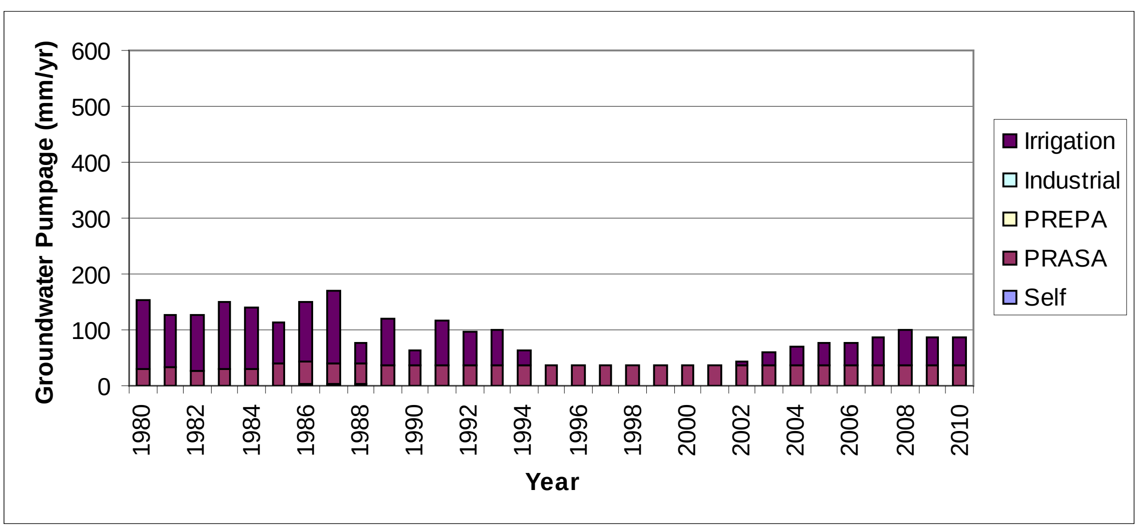

Figure 71. Estimated annual groundwater pumpage for Arroyo modeling area.

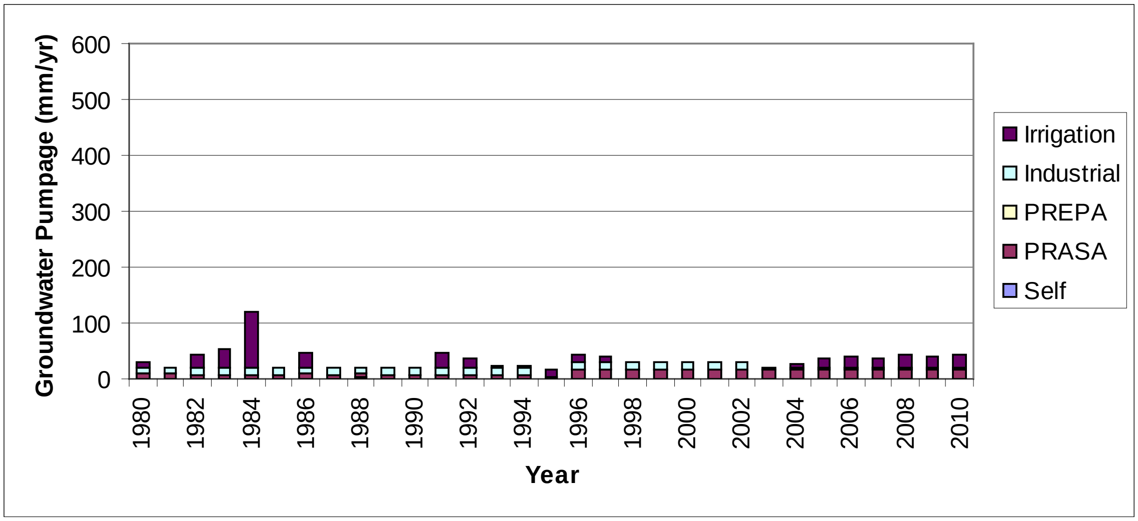

Figure 72. Estimated annual groundwater pumpage for Guayama modeling area.

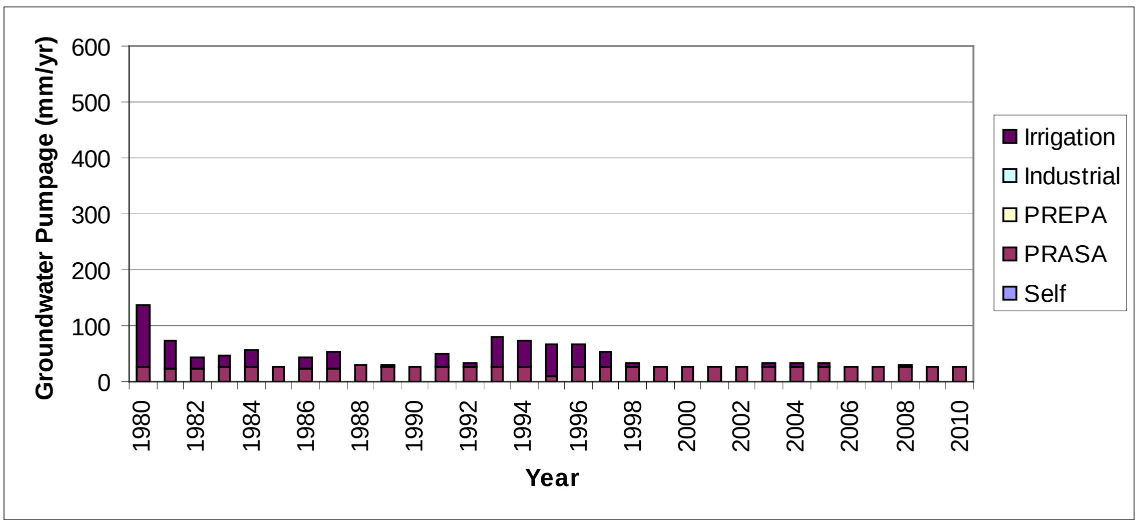

Figure 73. Estimated annual groundwater pumpage for Patillas modeling area.

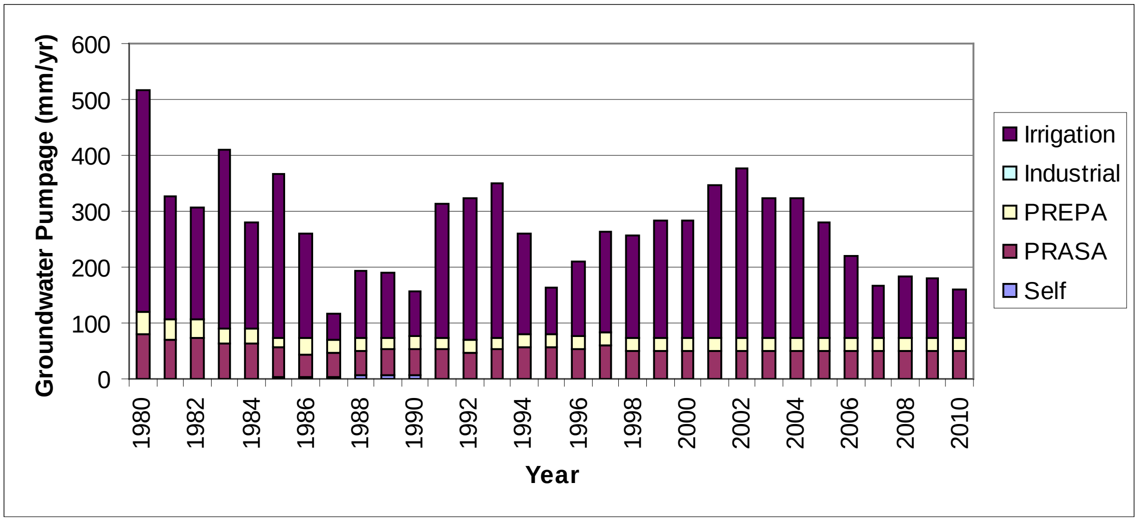

Figure 74. Estimated annual groundwater pumpage for Salinas modeling area.

Table 44. Estimated average annual pumpage, for irrigation periods between 1980 through 1993 and 1994 through 2010 per modeling area in mm/yr.

Area	**1980 - 1993**	**1994 - 2010**
Arroyo	121	59
Guayama	37	33
Patillas	52	38
Salinas	293	252

The developed model shows that the Salinas area experiences greater groundwater extractions than Guayama, Arroyo and Patillas. This is because its area counts with high hydraulic conductivity and a shallow and vast coastal water table aquifer that extent throughout the area between the Río Nigua de Salinas and the Río Guamaní in the vicinity of Guayama, which counts with favorable characteristics that do not exist past the Río Guamaní towards Guayama coastal plain and then are present again in Arroyo (Quiñones-Aponte *et al.*, 1997).

5.4 Aquifer Water Budget

The changes in aquifer storage and its possible groundwater interaction with the ocean were estimated based on an aquifer water budget model. The positive results from the difference between inputs and outputs to the aquifer are translated to groundwater recharge and/or groundwater leakage to the ocean and negative results from this difference is translated as groundwater depletion with the possibility of seawater intrusion.

In general, results from the model show a healthy aquifer in the Arroyo, Patillas and Guayama modeling areas in the sense that net recharge occurred the vast majority of the years with average net recharge rates grater than 180 mm/yr (Tables 45 and 46). In this modeling areas, groundwater depletion that might have resulted in seawater intrusion only occurred during the year 1980 due to the high groundwater extractions for irrigation purposes in a dry year that counted with below average precipitation and recharge. Arroyo and Guayama, respectively, experienced 18 and 24 percent decrease in net groundwater recharge between the periods prior and after the ending of sugarcane production in 1993 as direct result from the furrow irrigation sudden depletion. Although the Patillas area also experienced similar decrease in net groundwater recharge from irrigation practices after the 1993 year as Arroyo and Guayama did, Patillas actually experienced an increase of 25 percent in net groundwater recharge past the sugarcane termination. This is because in Patillas the termination of the sugarcane production represented an increase in flow from the Patillas reservoir, flow that before used to go through the irrigation canals. This greater outflow from the Patillas reservoir in great part was traduced to aquifer recharge in the Patillas coastal plane.

On the other hand, results form the model show an unhealthy South Coast aquifer in the Salinas area. According to model results, of this area, the groundwater depletion (to the point of possible saltwater intrusion) may have occurred during the years 1980, 1983, 1991, 1993, 1994, 1995, 1997, 2000, 2001, 2002, and 2009 due to the high water extractions for public supply and for agricultural practices. Contrary to the Arroyo, Guayama and Patillas modeling areas, the Salinas average net groundwater recharge did not change between irrigation periods (prior and after sugarcane termination) as shown in Table 45. This may be due to a combination of factors: 1) Groundwater pumpage in Salinas was kept fairly high because irrigation water pumpage was not greatly depleted after the ending of sugarcane production as the surface water imports did. 2) During the study period, the major contributor to groundwater recharge in Salinas were the streams

(Figure 70) especially in the 2000 to 2010 decade, on average, the recharge from streams was 18 percent higher than in the previous two decades which in proportionality have compensated for the 92 percent losses in irrigation percolation caused by changes in irrigated land and irrigation systems. The losses in irrigation percolation caused by changes in irrigated land and irrigation systems can be better explained using Table 46 where the reduction in irrigation percolation; in combination with a drier than usual decade, caused the net groundwater recharge to be reduced by 57 percent between the 1980s and 90s. Opposite to the 1990s, the 2000s was a wet decade where stream base flow was high which caused the average net groundwater recharge to increase by 42 percent from the 1990s, nonetheless this represents 25 percent lower than the average net groundwater recharge in the 1980s.

Table 45. Estimated average annual net groundwater recharge, for irrigation periods between 1980 - 1993 and 1994 - 2010 per modeling area in mm/yr.

Area	**1980 - 1993**	**1994 - 2010**
Arroyo	224	184
Guayama	301	229
Patillas	212	264
Salinas	64	64

Table 46. Estimated average annual net groundwater recharge per decade in mm/yr.

Area	**1980 - 1989**	**1990 - 1999**	**2000 - 2010**
Arroyo	212	201	195
Guayama	310	233	243
Patillas	205	236	276
Salinas	88	38	66

Figures 75 through 78 shows the results from the aquifer water budget estimates where “Net Recharge” refers to the combination of storage changes and sea-fresh water interactions as result of percolation minus pumpage.

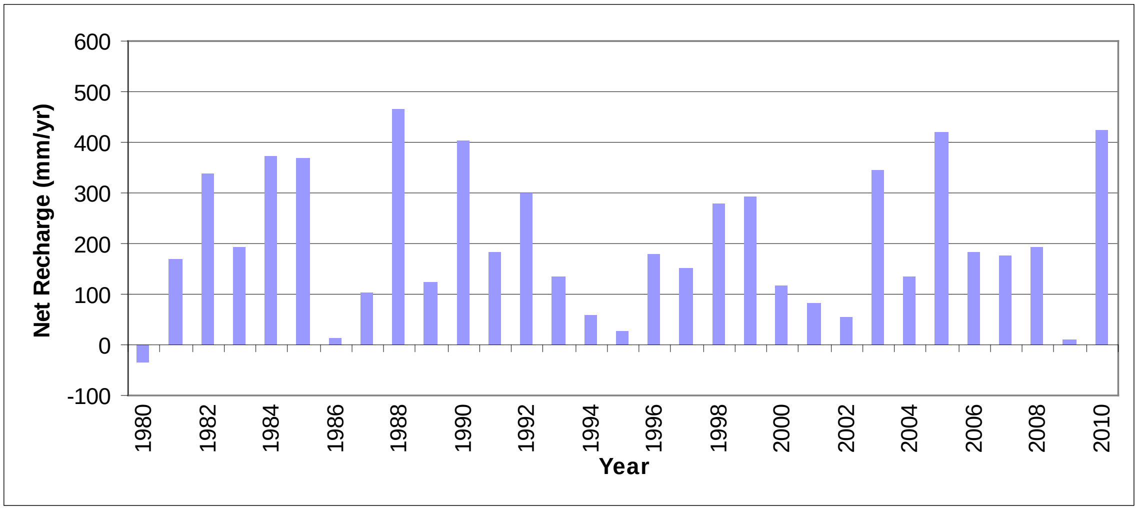

Figure 75. Estimated annual net groundwater recharge for Arroyo modeling area.

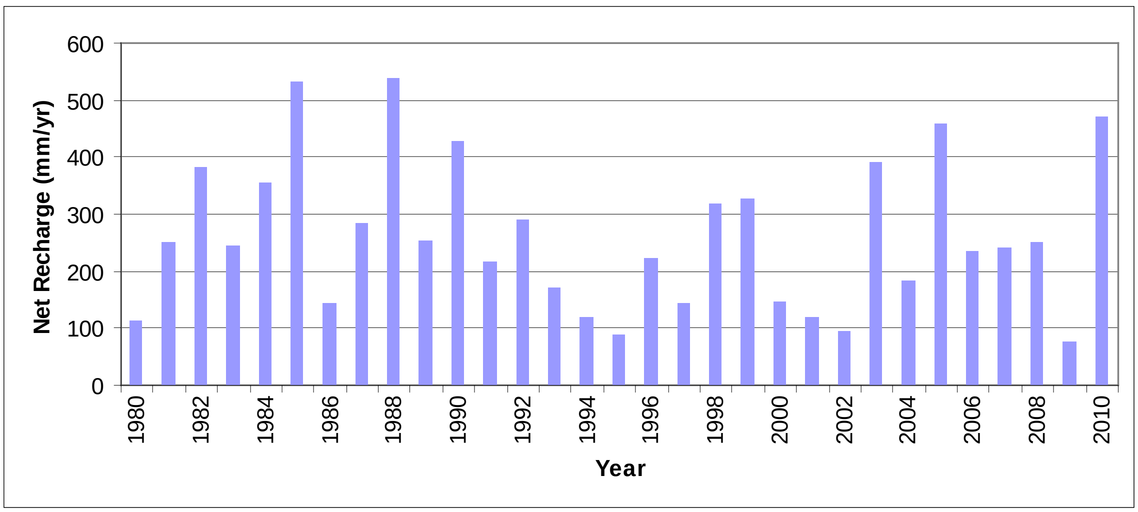

Figure 76. Estimated annual net groundwater recharge for Guayama modeling area.

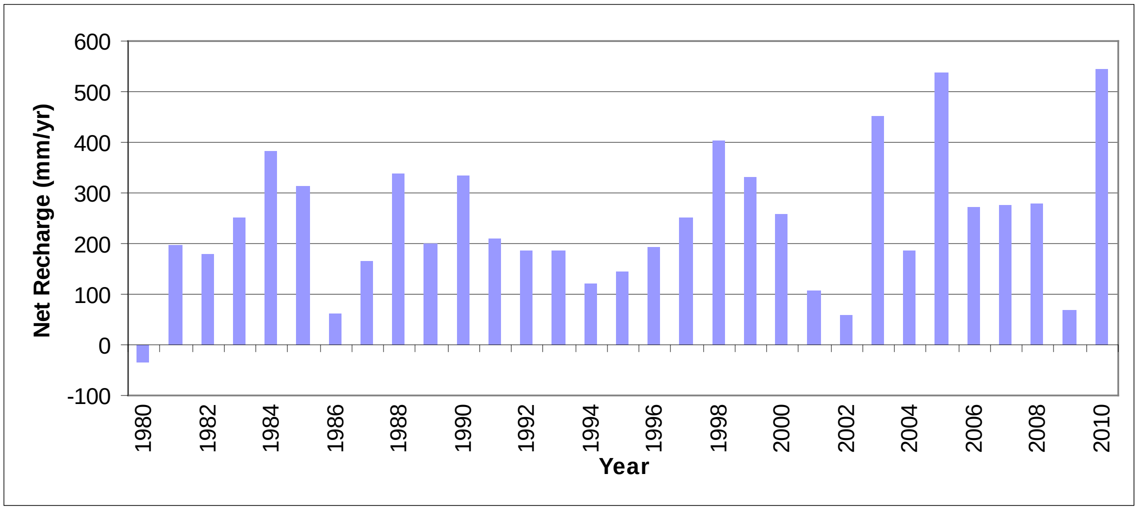

Figure 77. Estimated annual net groundwater recharge for Patillas modeling area.

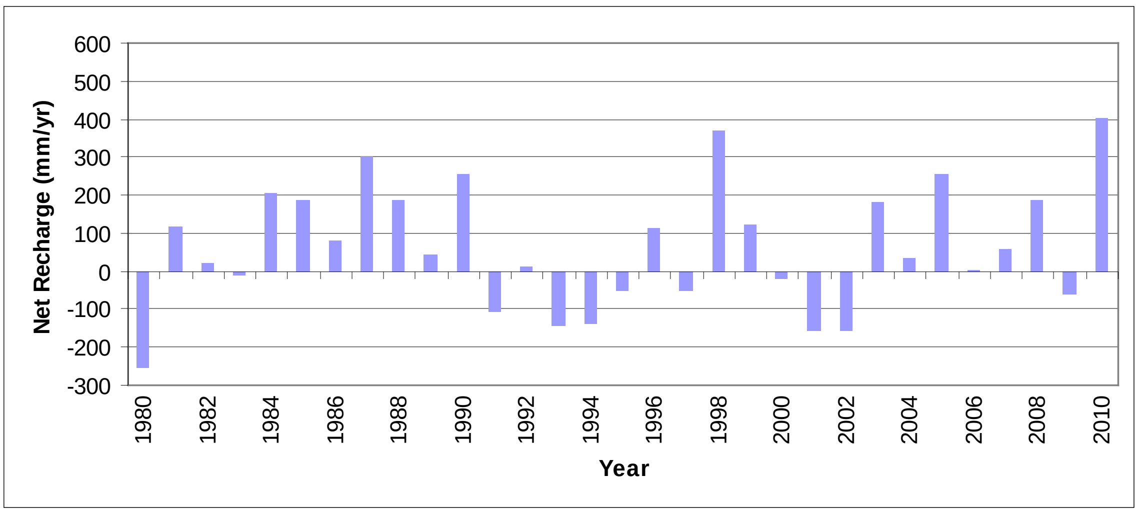

Figure 78. Estimated annual net groundwater recharge for Salinas modeling area.

5.5 Estimated Groundwater Recharge vs Piezometric Elevations

The relative accuracy of the model to estimate net groundwater recharge was assessed by comparing the results from net aquifer recharge estimates to piezometric depth (converted to elevation) obtained from the USGS Groundwater Watch: Puerto Rico Active Water Level Network. Although the model is not meant to estimate groundwater levels, it is expected that estimated monthly net recharge follow or mimic the recharge trend explicitly represented by the groundwater levels obtained as piezometric elevation. Positive net recharge for a monthly basis is expected to reduce or stop the depletion of the piezometric elevation in a standard basis or to increase the piezometric elevation in the case of big precipitation events. In Figures 79 through 83 this is translated to an increase in the slope created by piezometric elevations when plotted. On the opposite side, negative net recharge is expected to stimulate piezometric elevation depletion reflected in a decrease in slope when piezometric elevations are plotted.

The JBNERR east 2, Coquí, Rasa D and Aguirre wells in Salinas and the Juana well in Guayama were selected to validate the net recharge approach. The model simulated the changes in groundwater storage due to their difference in surface elevation which ranges from 1.5 to 41.2 meter above mean sea level. As expected, monthly net recharge results closely follow the piezometric elevation differences in the selected wells and in other wells in the Salinas and Guayama area.

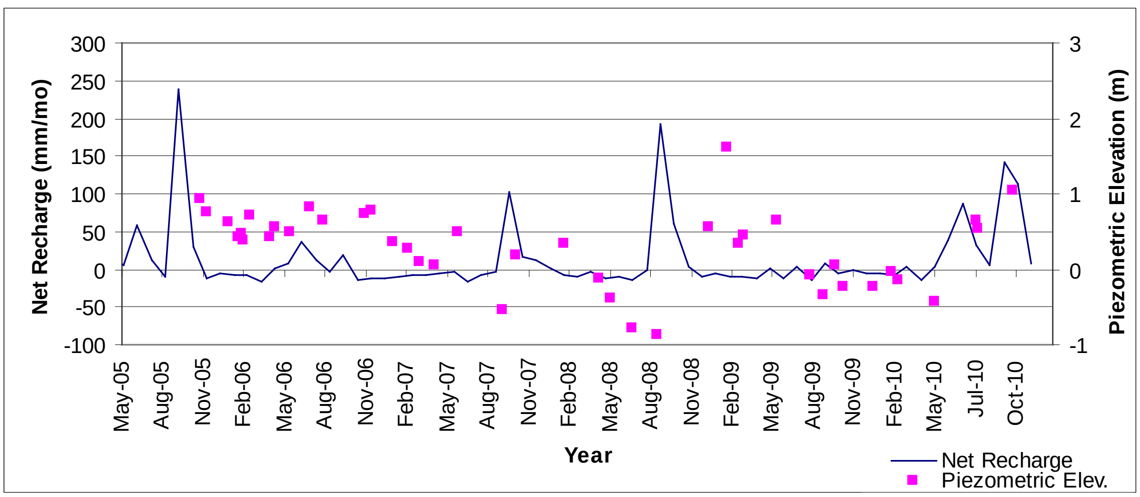

Figure 79. Estimated changes in storage represented by net recharge estimates compared to piezometric elevations for the JBNERR east 2 well in Salinas as measured periodically, 1.5 m surface elevation.

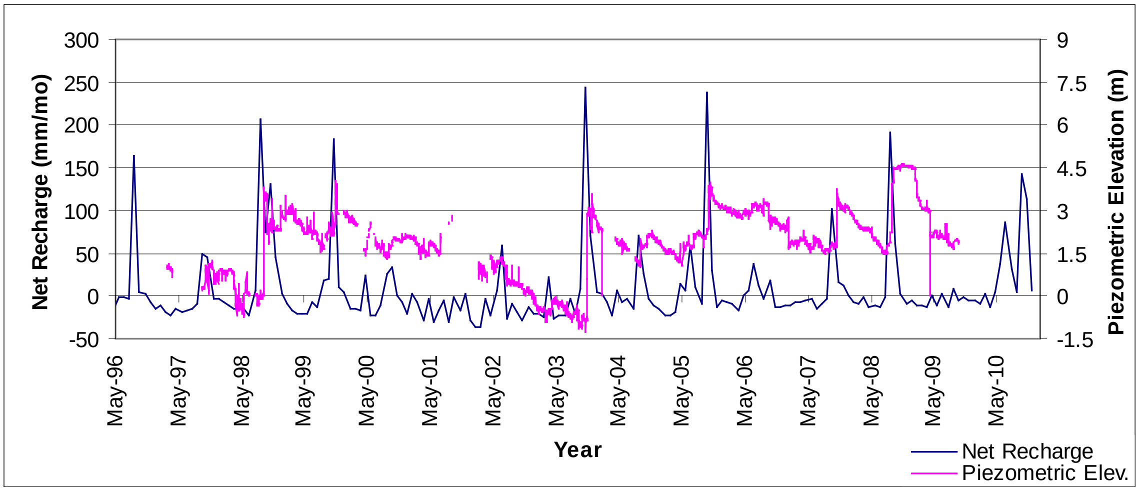

Figure 80. Estimated changes in storage represented by net recharge estimates compared to piezometric elevations for the Coquí well in Salinas as measured daily, 4.9 m surface elevation.

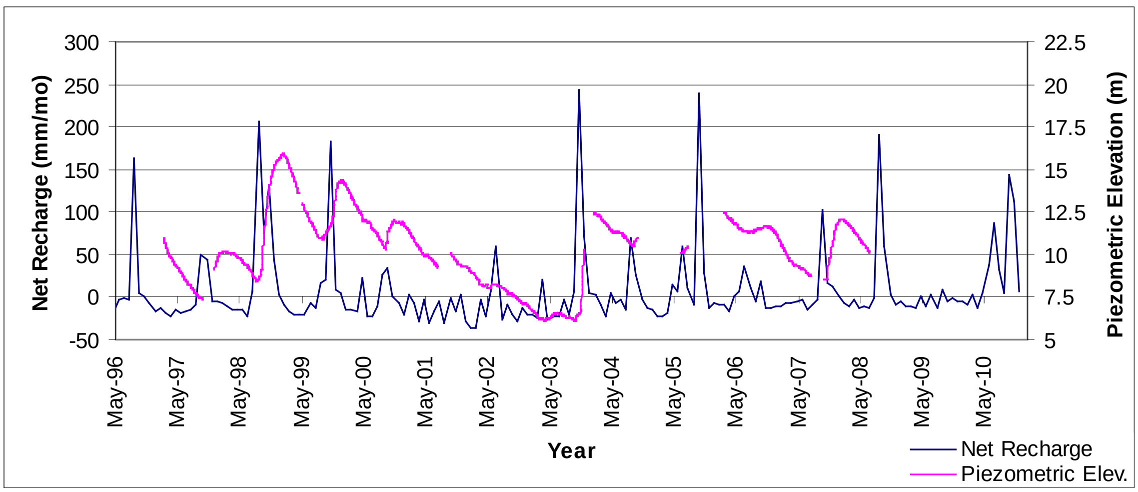

Figure 81. Estimated changes in storage represented by net recharge estimates compared to piezometric elevations for the Rasa D well in Salinas as measured daily, 27.4 m surface elevation.

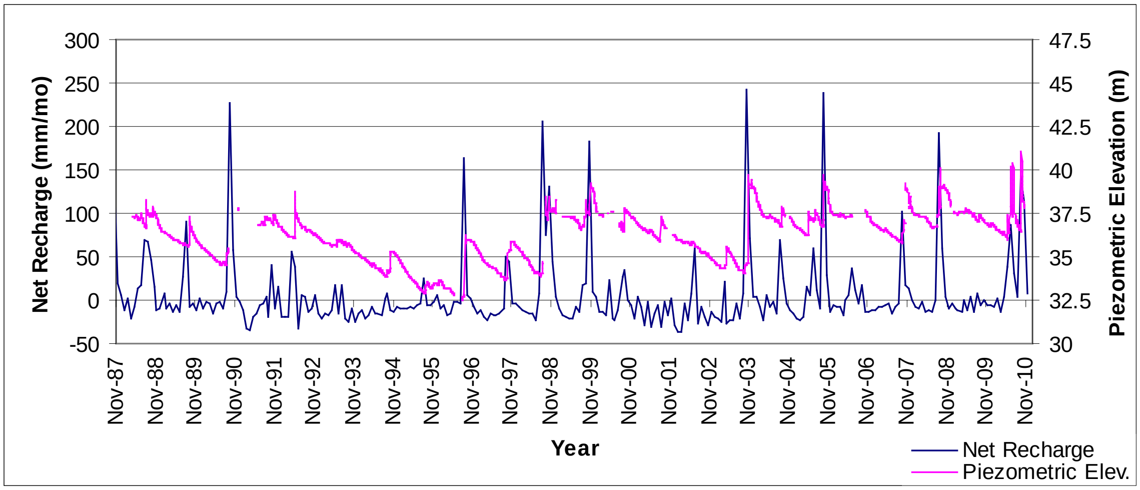

Figure 82. Estimated changes in storage represented by net recharge estimates compared to piezometric elevations for the Aguirre well in Salinas as measured daily, 41.2 m surface elevation.

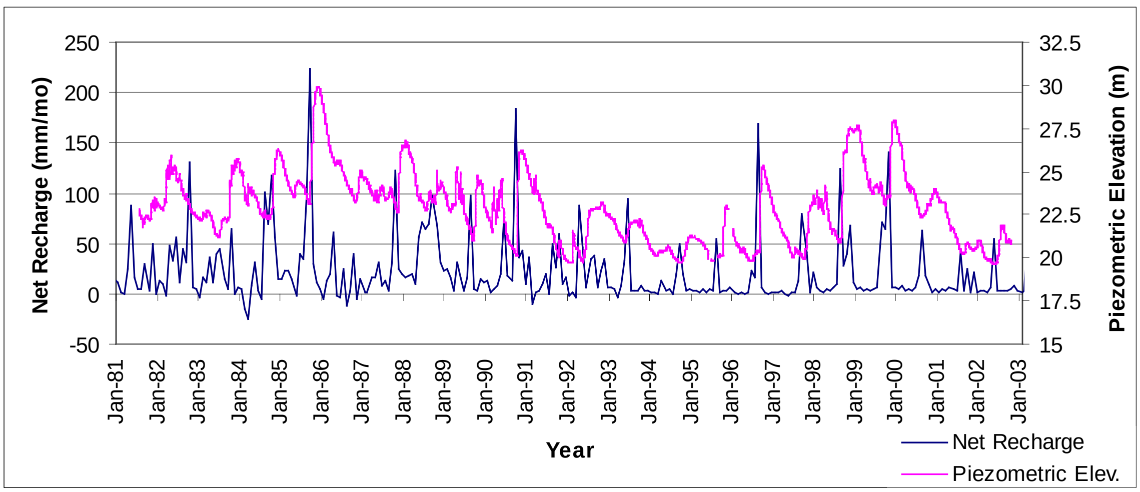

Figure 83. Estimated changes in storage represented by net recharge estimates compared to piezometric elevations for the Juana well as measured daily in Guayama, 39 m surface elevation.

5.6 Groundwater Recharge for the Irrigated Watersheds Modeling Area

The irrigated watersheds modeling area is nothing more than the conglomerate of the Arroyo, Guayama, Patillas and Salinas modeling areas. It represents the global status of the system and summarizes inputs and outputs by municipality which data can be used in the decision making process when dealing with the management of the water resources of the area. Figures 84 through 91 show the contribution from each modeling area to the South Coast Aquifer net recharge.

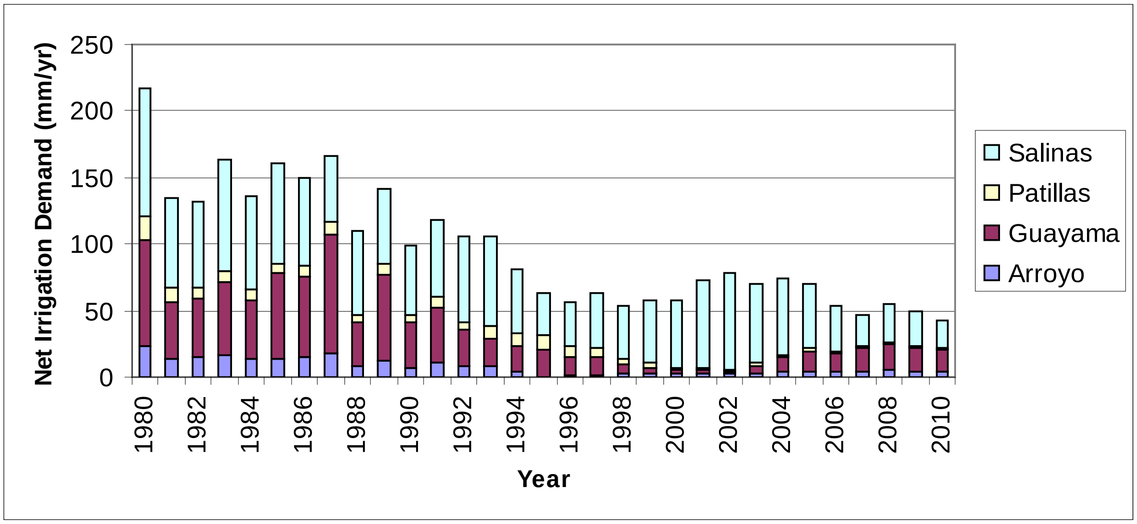

Figure 84. Estimated net irrigation water demand for the Irrigated Watersheds modeling area.

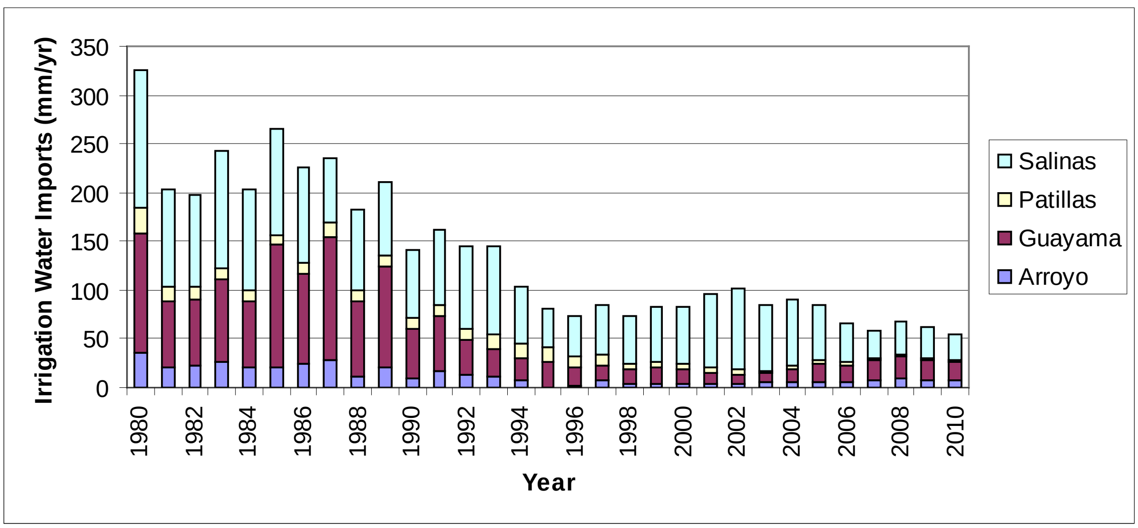

Figure 85. Estimated irrigation water deliveries by PREPA to the Irrigated Watersheds modeling area.

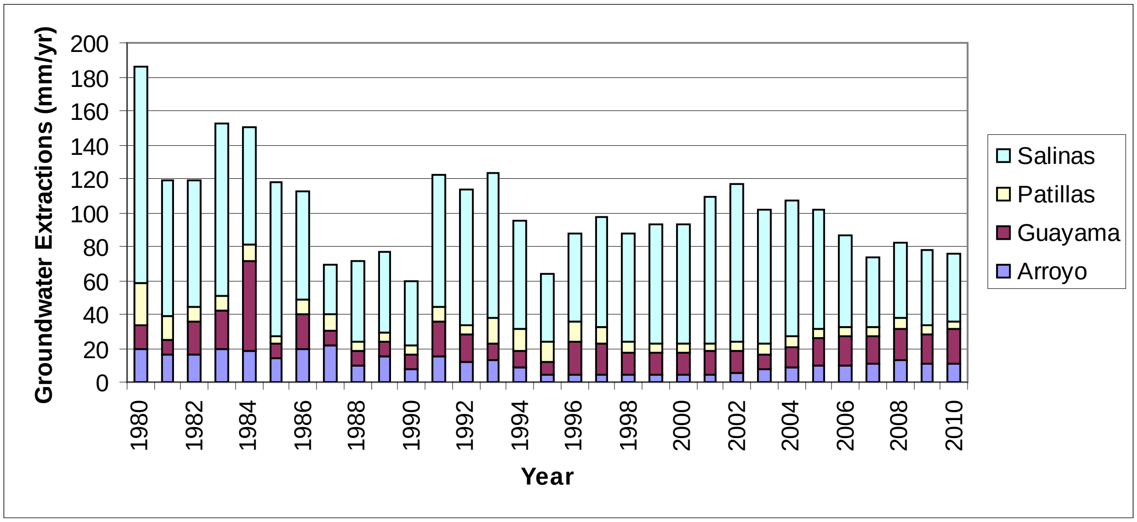

Figure 86. Estimated groundwater extractions for irrigation purposes for the Irrigated Watersheds modeling area.

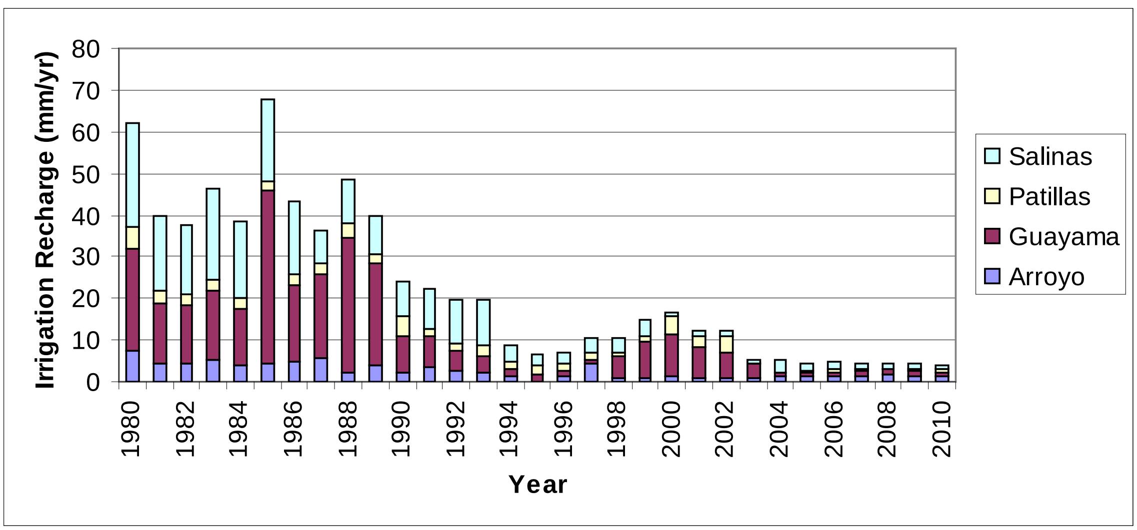

Figure 87. Estimated recharge from irrigation percolation for the Irrigated Watersheds modeling area.

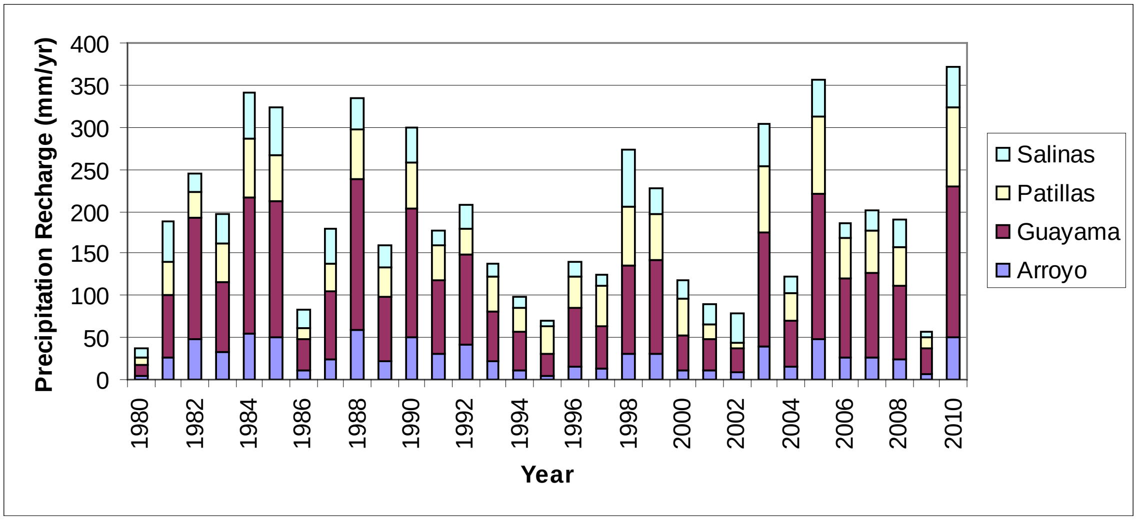

Figure 88. Estimated recharge from precipitation percolation for the Irrigated Watersheds modeling area.

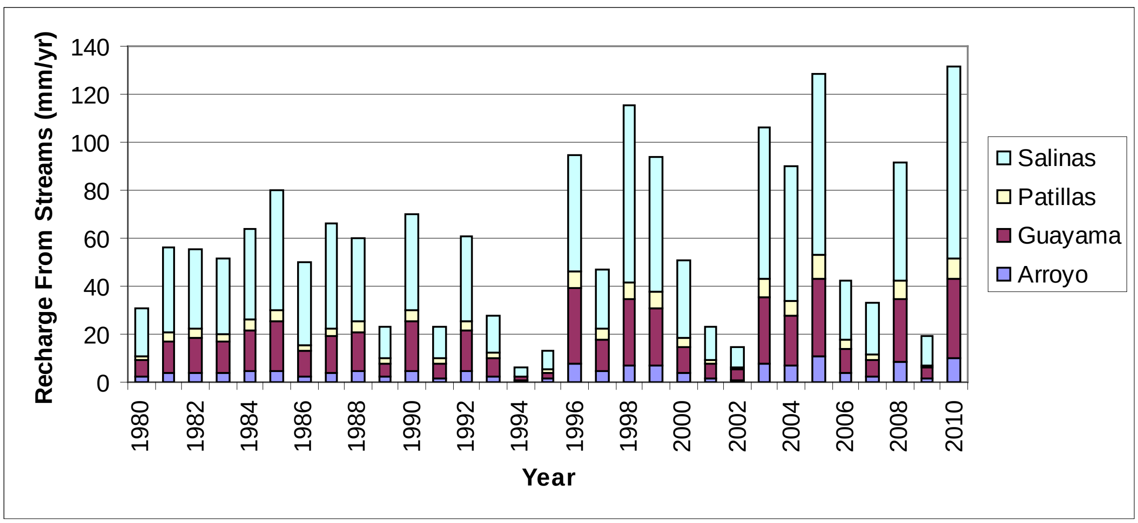

Figure 89. Estimated recharge from stream base flow percolation for the Irrigated Watersheds modeling area.

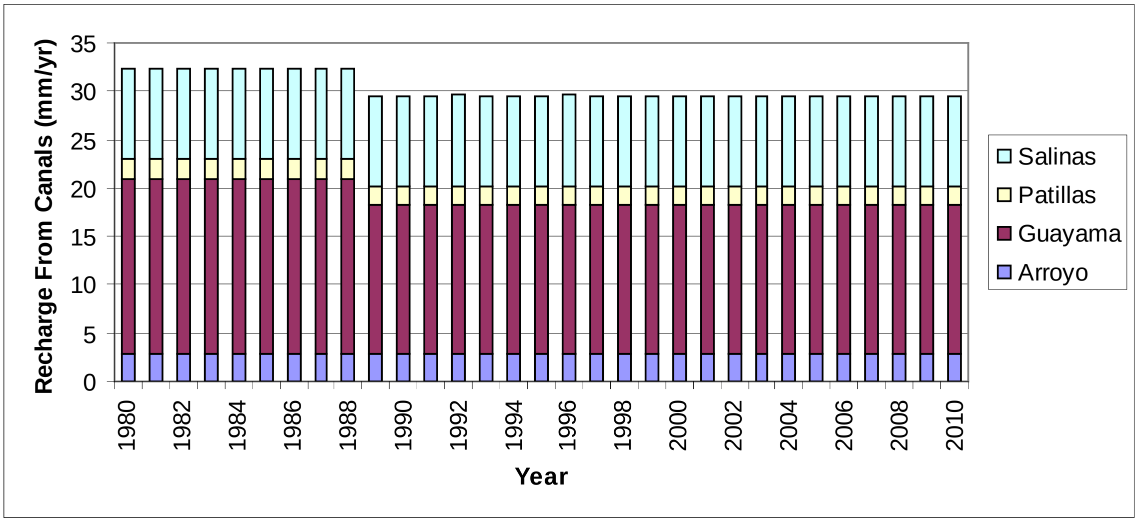

Figure 90. Estimated recharge from irrigation canals percolation for the Irrigated Watersheds modeling area.

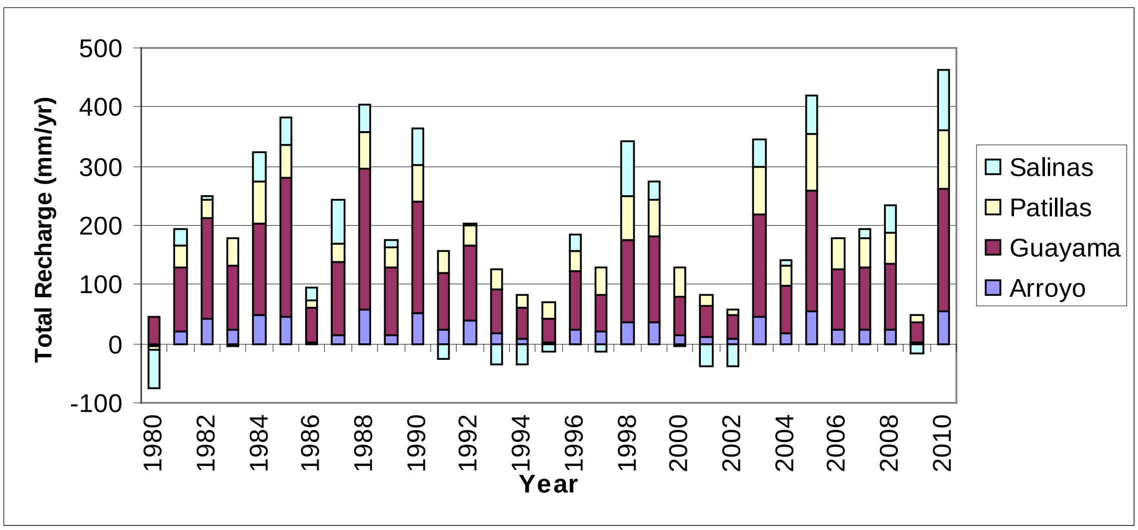

Figure 91. Estimated global recharge from percolation for the Irrigated Watersheds modeling area.

5.7 Estimated Monthly Recharge Distribution

The net groundwater recharge distribution within a year might be an important factor to be considered in ground and surface water management. Capiel and Calvesbert (1976) stated that in the Puerto Rico south coast, most groundwater recharge occurs during the wet season between May and November.

Results from the monthly net groundwater recharge model of the current study (aquifer budget model) showed that around 95 percent of the net groundwater recharge occurs within these months and that groundwater depletion occurs from the end of January to the beginning of April, being March the most critical month. The heavier recharge inputs to aquifer recharge occur within the months of September, October and November, been October the most favorable month. This behavior is expected been March the driest month of the year and October the wettest (Figures 92 and 95).

Typically, net recharge is low or negative during the first quarter of the year. Recharge gradually increases during the second quarter of the year from April through July, drops in August to then greatly increase in September and October where it reaches its peak, to then drop in November and December. The Arroyo and Salinas area historically have experienced negative net groundwater recharge during the first quarter of the year (Figures 92 and 95). In Patillas (Figure 94), negative net groundwater recharge has occurred mostly during the month of March, while Guayama (Figure 93) have rarely experienced negative net groundwater recharge according to the model. In Salinas, groundwater depletion might be critical during the period between December and May when is estimated that the aquifer is in constant and repeated stress.

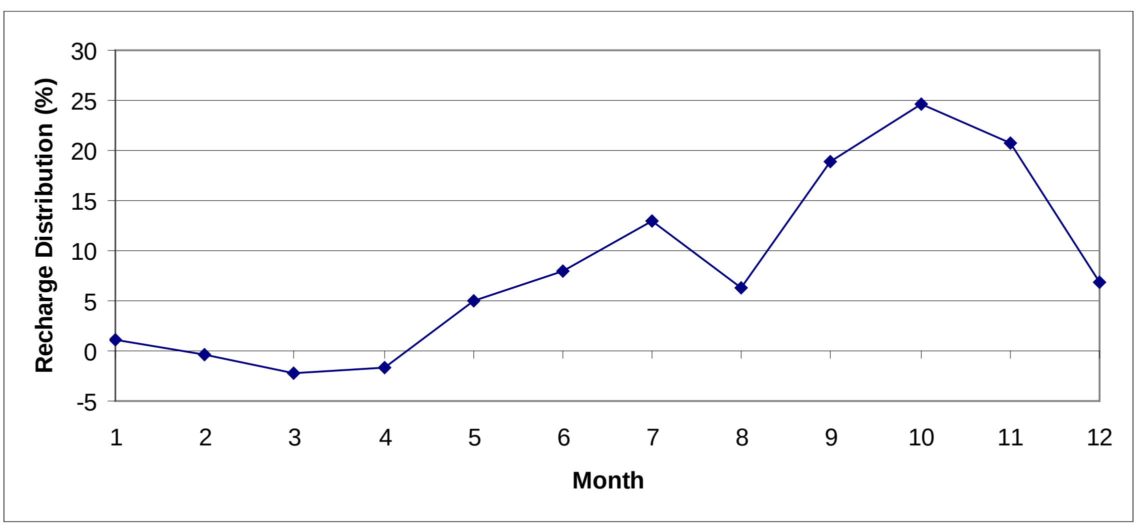

Figure 92. Estimated average net recharge distribution by month in Arroyo modeling area.

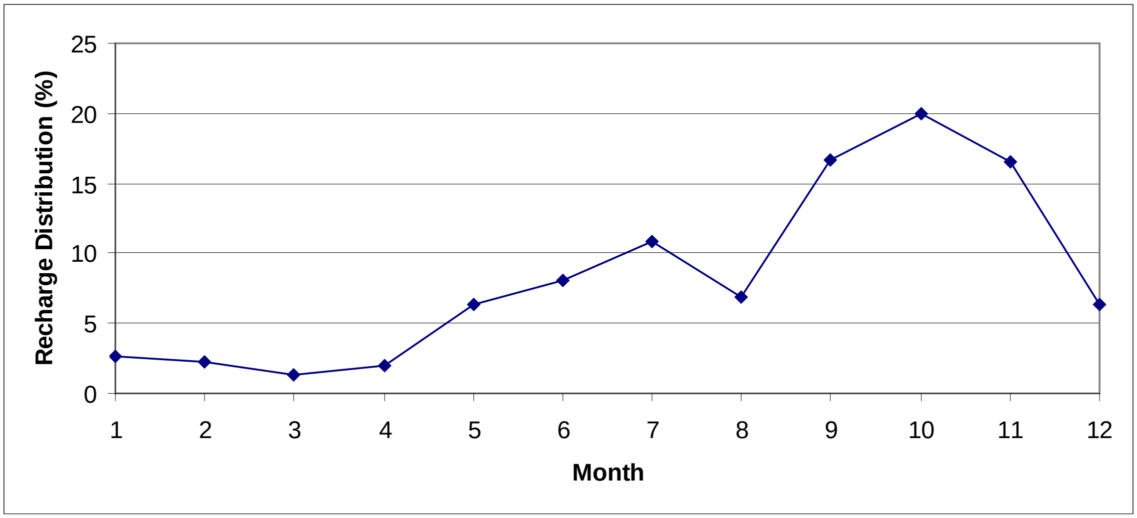

Figure 93. Estimated average net recharge distribution by month in Guayama modeling area.

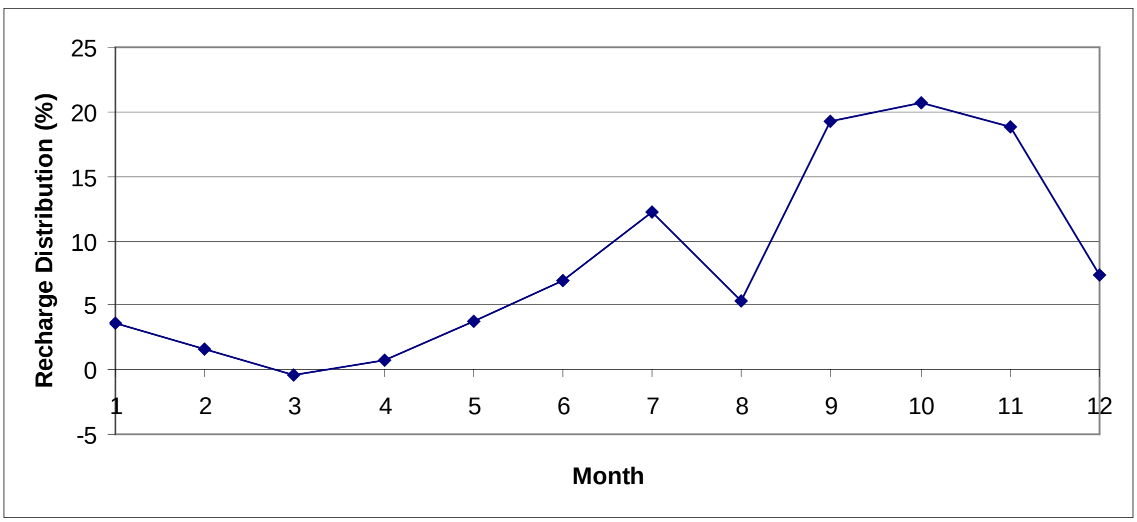

Figure 94: Estimated average net recharge distribution by month in Patillas modeling area.

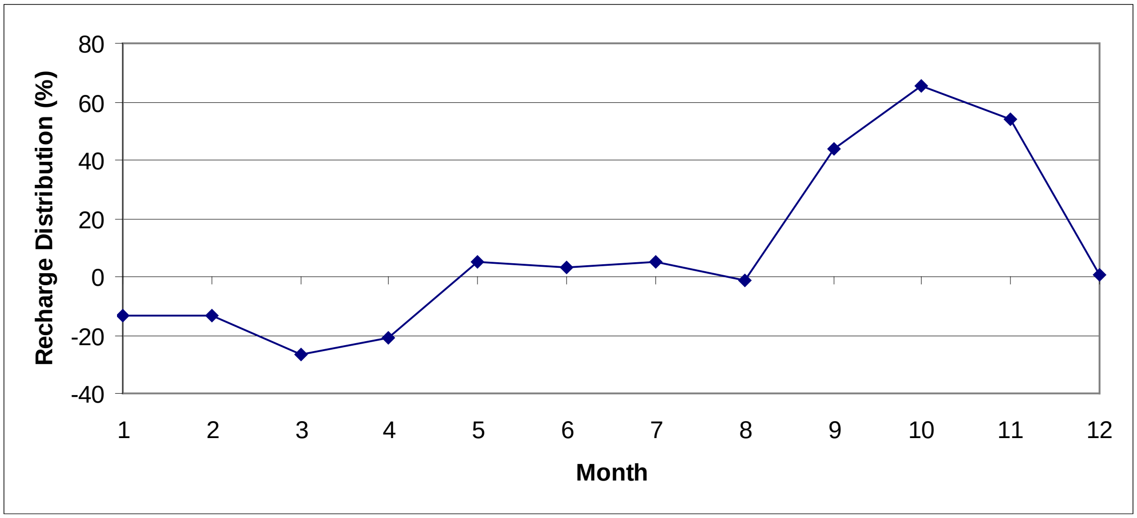

Figure 95. Estimated average net recharges distribution by month in Salinas modeling area.

5.8 Relative Importance of Each Recharge Input

The relative importance or contribution of each recharge factor as a fraction of the complete recharge might be another aspect to consider in surface and groundwater management. In the Arroyo, Guayama and Patillas area, precipitation is by far the most important factor in aquifer recharge (Figures 96, 97 and 98) even during dry years in which streams, canals and irrigation water gain importance. For most of the years, precipitation constituted about 70 percent of total recharge in the Arroyo, Guayama and Patillas area. During dry years as it was 1986, 1995, 2002 and 2009, recharge from irrigation canals comes to be the second most important factor in aquifer recharge in the Guayama area while in Patillas and Arroyo this is not necessary true. In the Salinas area (Figure 99) streams and precipitation exchange the order of importance for the factor of major influence in aquifer recharge and while irrigation was an important factor in the 1980s, when it provided about 20 percent of the aquifer recharge and it has become insignificant in the 2000s where canal infiltration has replace it. Table 47 summarizes the relative input that each percolation factor contributes to the aquifer recharge expressed as percentage of the total.

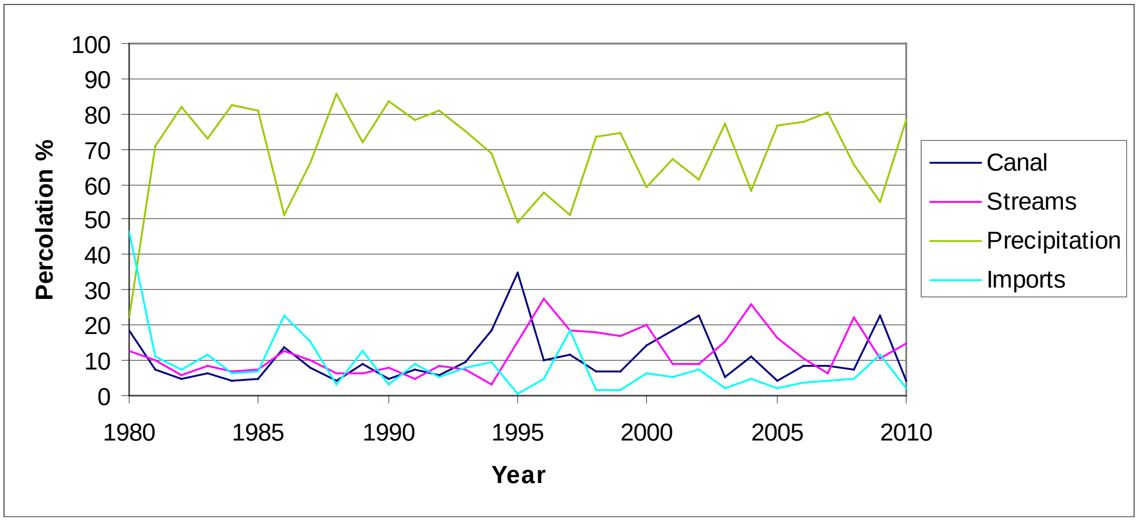

Figure 96. Relative importance of each percolation factor to aquifer recharge for the Arroyo modeling area in an annual basis.

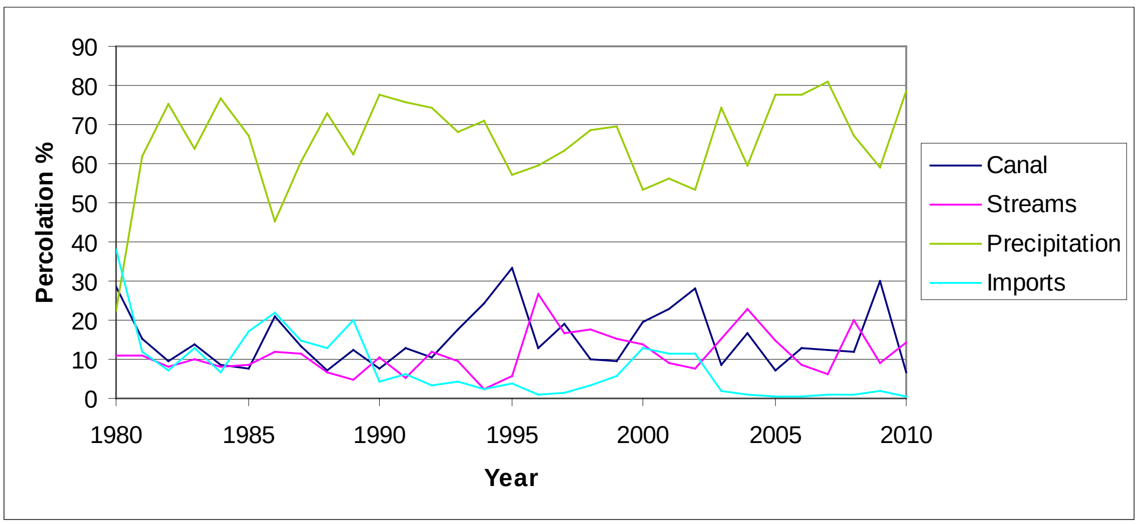

Figure 97. Relative importance of each percolation factor to aquifer recharge for the Guayama modeling area in an annual basis.

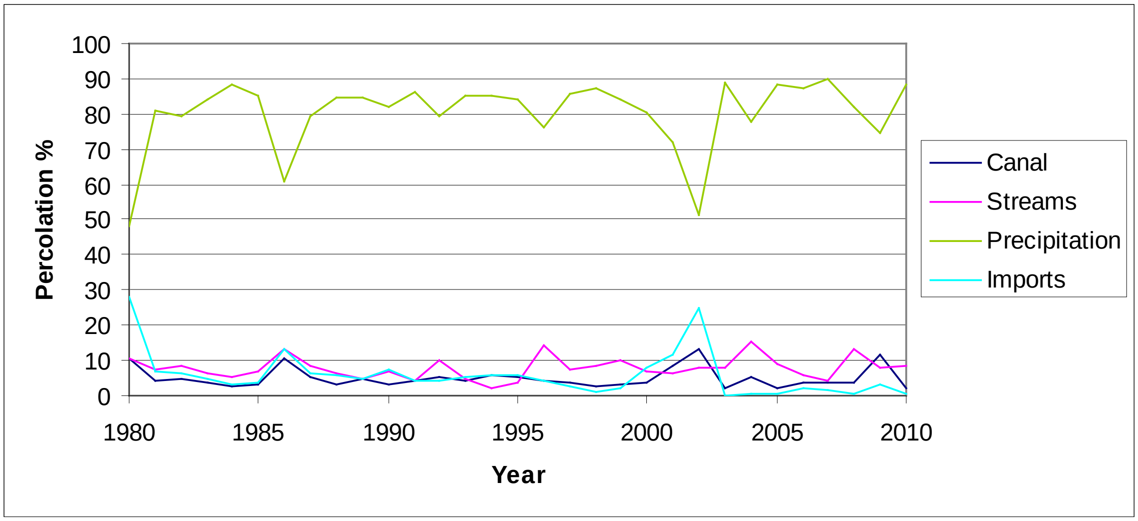

Figure 98. Relative importance of each percolation factor to aquifer recharge for the Patillas modeling area in an annual basis.

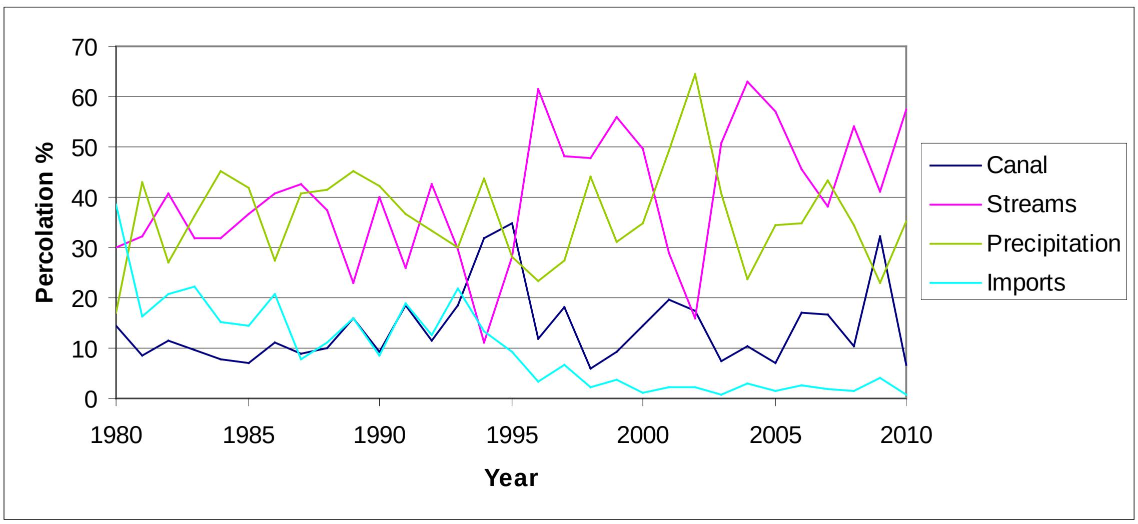

Figure 99. Relative importance of each percolation factor to aquifer recharge for the Salinas modeling area in an annual basis.

Table 47. Estimated average annual groundwater recharge distribution per input per modeling area expressed as percentage of total percolation.[40]

Area	**Precipitation (%)**	**Streams (%)**	**Irrigation (%)**	**Canal (%)**
Arroyo	69	12	8	11
Guayama	65	11	8	15
Patillas	80	8	6	5
Salinas	36	40	10	14

40 - For the entire study period

5.9 Groundwater Management Scenarios for Salinas

According to the modeling results, the Salinas modeling area experiences the most critical scenario in terms of groundwater net recharge along the eastern part of the South Coast Aquifer. The combination of low precipitation with high groundwater pumpage for irrigation, public supply and for thermoelectric plants, in which, added to a decrease in return flow from irrigation have created serious problems to the Jobos Bay ecosystem (Kuniansky and Rodríguez, 2010). It also, has caused groundwater depletion cones that reach below mean sea level at the lower elevations near the ocean as shown in Figures 79 and 80. According to Kuniansky and Rodríguez (2010) one of the most noticeable changes in groundwater resurface and coastal leakage is that since 1990, about 30 hectares of black mangroves have died in the Jobos Bay National Estuarine Research Reserve (JBNERR) in coastal Salinas.

Stream base flow; which is estimated to be the main source of groundwater recharge during the most recent decade, is dependent on the precipitation on the Río Majada basin that in the developed model is represented by rain depth measured at the Jájome Alto weather station in the upper part of the basin and the Aguirre weather station in the lower part. On average, Salinas receives about 25 to 35 percent less recharge from precipitation than Arroyo, Guayama and Patillas, although it receives 30 percent more recharge from streams. Groundwater recharge from the Patillas-Guamaní irrigation canals, constituting about 10 percent of the total recharge to the aquifer in the Salinas area, represents a solid and constant source that maintains the aquifer well being.

Because out of the four sources of groundwater recharge in the Salinas area, the Patillas-Guamaní irrigation canals are believed to be the most constant and secure source of water, two scenarios are presented as possible strategies for groundwater management in the area involving these irrigation canals and assuming that their development are feasible. These alternatives are: 1) increase surface water imports from the canals to farms and decrease or eliminate groundwater extractions for irrigation practices, 2) create infiltration ponds that uses collected runoff and exceeding water from irrigation canal as a source of aquifer recharge in strategic areas. Both alternatives are presented and discussed under present conditions but using historical precipitation and temperature data. This is done with the intention of using historical data as base of consideration on what would happen in the future if these changes occur.

Alternative one for groundwater management in the Salinas area: increase surface water imports from the irrigation canals and decrease or eliminate groundwater extractions for irrigation purposes is presented under the assumption that the development in terms of reconstruction and remodeling of the canals is feasible and that the Patillas and Carite reservoirs still can deliver the amount of water to the canals for irrigation as were designed for.

The alternative of reducing or eliminating groundwater extractions in the coastal Salinas have been presented in various forums and is one of the alternatives suggested by Kuniansky and Rodríguez (2010). Eliminating groundwater pumpage is an extreme measure. The fact that PRASA serves the Salinas population from this source, and the thermoelectric plants operated by PREPA in Salinas; which serve energy to more than a million people, cool down its turbines using this water make this idea almost impossible. Opposite to reducing or eliminating groundwater extractions from PRASA for public supply and/or from PREPA for thermoelectric generation, it is conceivable to considerably reduce or eliminate groundwater pumpage for irrigation purposes. This is because of the existence of the irrigation canals which (if reconstructed and/or remodeled) can serve water to the farms in the Salinas area. This would serve a double purpose: reduce groundwater extraction and foment groundwater return flow from irrigation and recharge from the canals.

During the past decade only about 10 percent of the irrigation water requirement in the Salinas area was imported from the irrigation canals while in the 1980s was up to 83 percent (Figure 100). Water management in the area could be planned in such a way that the Guayama Irrigation District of PREPA could provide between 75 and 100 percent of the water requirement by crops in the Salinas area. This kind of practice is already in use by many irrigation districts in the United States and has been already done in the past within the study area when the Guayama Irrigation District used to provide 4900 m^3 of irrigation water per 0.4 hectares of cropped land per year (4 ac-ft of water per acre of crop per year) to farmers. This amount of water is translated to over 1,200 mm of water per year; which means that, in average, 93 percent of the irrigation water requirement would be satisfied by irrigation water imports from PREPA.

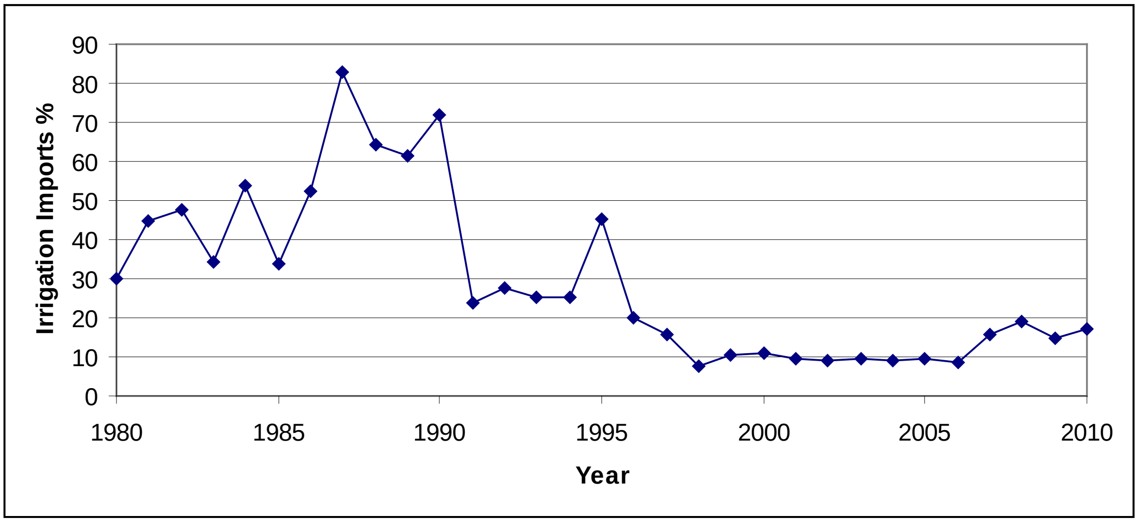

Figure 100. Changes in irrigation water imports to farms for irrigation by PREPA as a fraction of irrigation water requirement for Salinas modeling area.

A simple approach was implemented to evaluate groundwater recharge under different precipitation scenarios. Data for irrigated area, irrigation efficiency, percolation from irrigation, soil moisture allowable depletion, crop evaporation coefficient, effective root depth, Curve Numbers and canal percolation for the year 2010 was used as it was for modeling inputs for the entire 31 year study period. On the other hand, daily maximum and minimum temperature, daily precipitation, estimated monthly and annual percolation from streams, soil field capacity, soil depth and watershed area was kept unchanged. Irrigation water imports from PREPA was set to be 100, 93 and 75 percent the estimated irrigation water requirement to simulate that none, 7 and 25 percent of the irrigation requirement is provided by groundwater pumpage, respectively.

If groundwater extractions for irrigation purposes ceases and all other conditions continue as they were in the second part of the 2000s, the Salinas area very likely will experience a very good net recharge to the aquifer and a coastal groundwater outflow favorable for the Jobos ecosystems. Figure 101 show how net groundwater recharge and coastal leakage would behave under the precipitation conditions from the past 31 years. If today's conditions are extrapolated historically, under no groundwater extractions for irrigation purposes, even the driest years such as 1980, 1994, 1995 and 2009 would receive a positive net recharge. As wonderful as these sounds, reach this goal would mean a great investment in canal infrastructure. Irrigation canals would have to deliver as much water to the area as they were design for, this is between 6 and 8 times more water than what was delivered annually during the second part of the 2000s. Canal reconstruction, re-layout and expansion would have to take place and probably they would have to be re-build impermeable to be able to deliver this amount of water and also satisfy irrigation water requirements for Guayama, Arroyo and Patillas and water requirements for PRASA intakes along the canals.

During the study period, the worst case scenario in terms precipitation distribution and groundwater recharge is represented by the year 1995. Even during this year the estimated irrigation water requirement under today's conditions is estimated to be 1,555 mm, where the irrigation canals would be able to provide 74 percent of it.

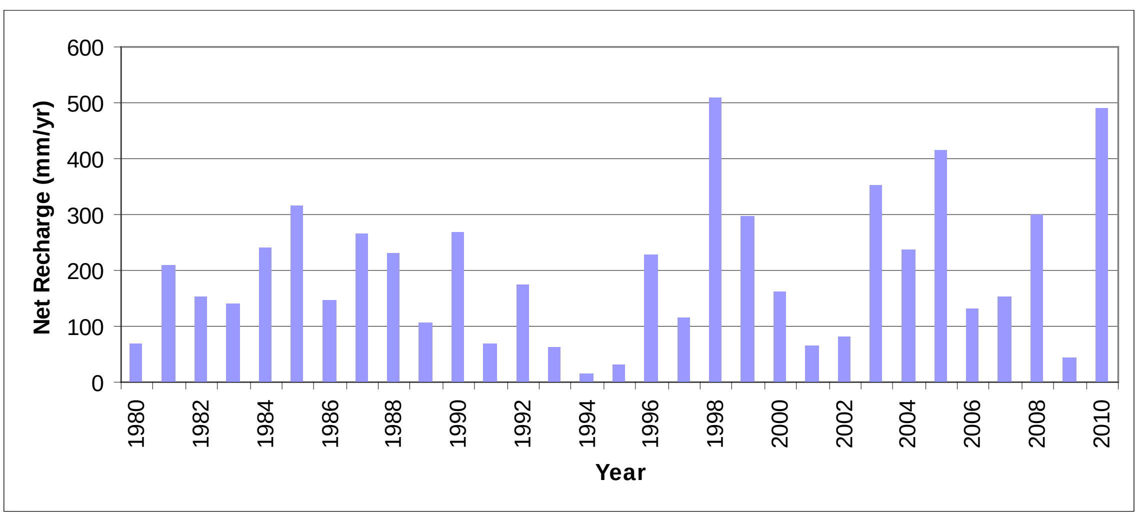

Figure 101. Case scenario where no groundwater pumpage for irrigation purposes take place and all irrigation water is retrieved from canals, based on an extrapolation of today's irrigation conditions to historical data.

Aware that it might be impossible and/or no feasible to set the canals such that the water can be delivered to all irrigated areas, two more realistic scenarios are presented where water deliveries from canals could satisfy 93 and 75 percent of the irrigation water requirements in the area and 7 and 25 percent of the irrigation water requirements would have to be provided by groundwater pumpage (Figures 102 and 103). Both case scenarios still produce very good aquifer recharge under the established conditions. However, in extreme draught as happened in the years 1980, 1994 and 1995, irrigation deficit or irrigation abandonment would have to be required in order to secure positive net groundwater recharge. Still, irrigation canals would have to be remodeled and rigorous irrigation planning and management have to be established for the system to be able to deliver 1,200 mm of irrigation water per year to 75 percent or more of the irrigated areas.

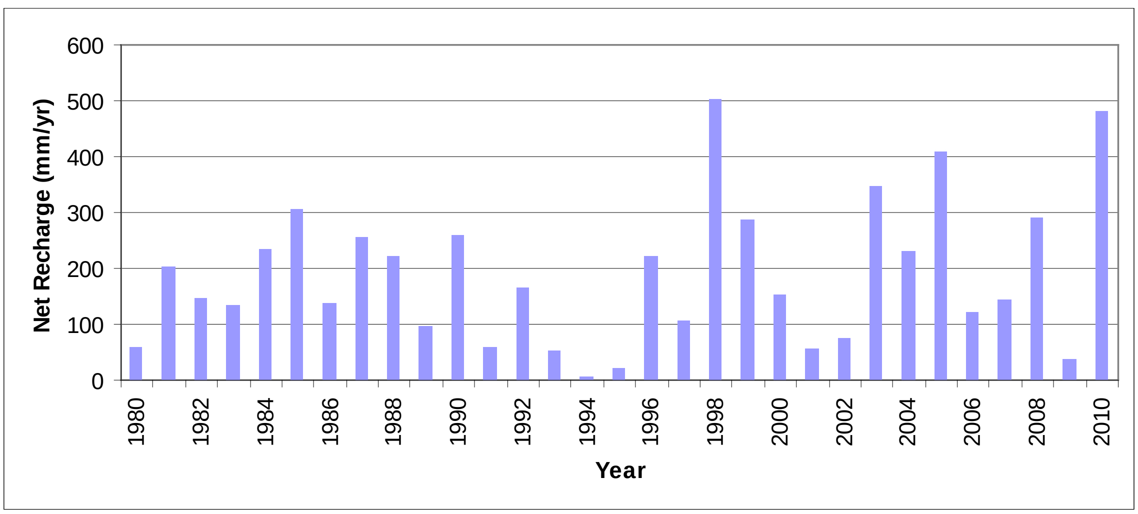

Figure 102. Case scenario where 7% of groundwater pumpage for irrigation purposes take place and all other irrigation water is retrieved from canals, based on an extrapolation of today's irrigation conditions to historical data.

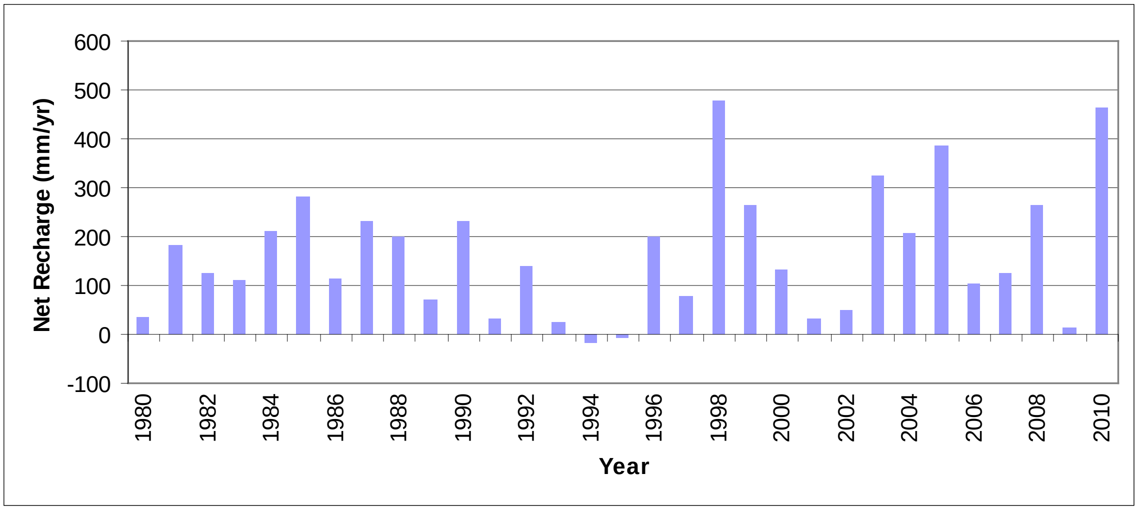

Figure 103. Case scenario where 25 % of groundwater pumpage for irrigation purposes take place and all other irrigation water is retrieved from canals, based on an extrapolation of today's irrigation conditions to historical data.

Establishing infiltration ponds that use a combination of collected runoff, water from irrigation canals and treated wastewater might be a more feasible practice than reducing or eliminating irrigation water pumpage in the Salinas area. Infiltration ponds located in strategic areas of high infiltration in the inner valley can greatly contribute to aquifer recharge. As the previous groundwater management alternative, this one was evaluated extrapolating the most recent conditions (year 2010) to the precipitation and temperature conditions that prevailed annually from 1980 through 2010.

With the goal of achieving positive net recharge in worst case scenarios as it was in 1995, but under today's conditions, the allocation of shallow infiltration ponds of a total volume of 12,335 m^3 in size was evaluated. Although the dimensions may vary, the volume is suggest because 12,335 m^3 is the allowable volume that a water storage facility can hold without been considered a dam. The strategy for achieving this goal is to set the biggest infiltration pond possible in an area with a permeability of 35 mm/day or higher that would produce groundwater percolation for least 315 days a year. It was found that the use of 2 shallow infiltration ponds of a total volume of 12,335 m^3 that are constantly feeding the aquifer with percolated water produce positive net groundwater recharge even in the worst case scenarios and could increase the average net recharge from 64 to 236 mm/year (Figure 104). This increase in three and a half times the average net groundwater recharge certainly will secure the necessary flow for the Jobos ecosystem to succeed.

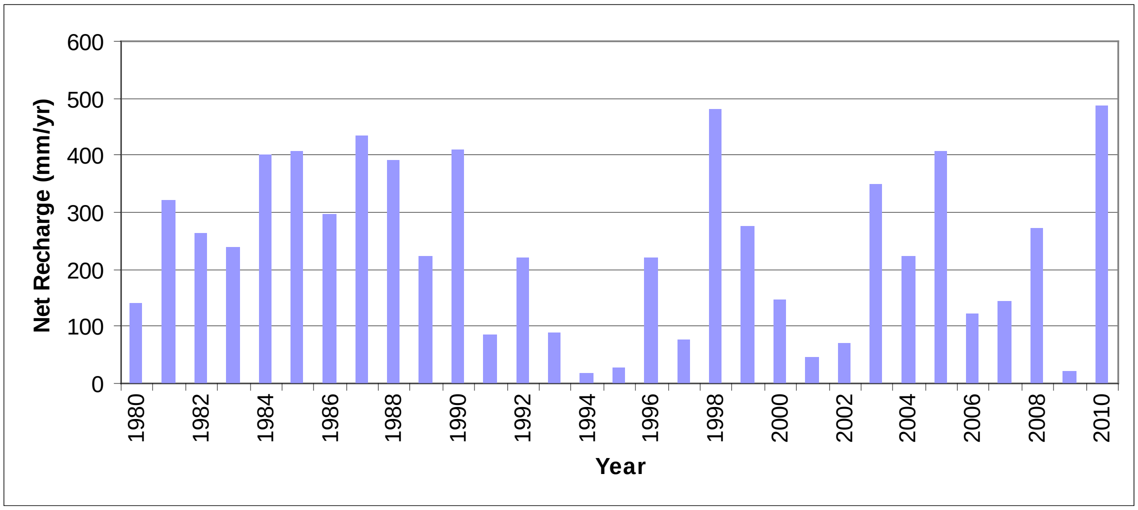

Figure 104. Case scenario where 2 infiltration ponds of the already mentioned conditions are established to support groundwater recharge based on historical data.

5.10 Sensitivity Analysis

Water balance methods combine several models and they are sensitive to the parameters and inputs of each of the models (Brush *et al*., 2004). Parameters of the soil surface process model, like the NRCS Runoff Model that includes the curve number and land conditions along with antecedent soil moisture content, can be affected by precipitation and actual evapotranspiration. Parameters of the soil moisture budget include a uniform field capacity along a particular soil, uniform rooting depth among crops and forest, uniform crop life length, forest and wetland uniformity, the evapotranspiration coefficients (Kc) for each land cover along with land cover areas, and irrigation water deliveries. The chosen sensitivity analysis method assesses what effect uncertainties in each of the input parameters will have on the model's output.

The ten parameters shown in Table 48 were selected as the most sensible parameters to the model and the ones that introduce the greater error, under the assumption that the most significant input variables are those with 10 percent variation, in average causes a 1 percent or greater change in the model outputs or results. These sensitivities are reported here as percent change in the average annual recharge rate in response to a 10 percent change in the input parameter. The sensitivity of the water budget model to the groundwater pumpage (PRASA and PREPA), curve number (AMC 3 NI and AMC 2 NI), evapotranspiration coefficients (Kc I and Kc NI), percolation from irrigation practices (I perc), soil maximum available water or field capacity (θ), irrigated area (I area) and crop effective root depth (Eff. R I) are believed to be the most sensible factors. Out of this parameters ground water pumpage from the Puerto Rico Aqueduct and Sewer Agency (PRASA) and the antecedent moisture content for normal conditions on non irrigated (NI) areas (AMC 2 NI) produced the greater and lesser variations to the model output, respectively. Although the sensitivity of the parameters varies from year to year, average sensitivities were used in the determination of the most sensible factors. Annual results from the ten factors selected as the most sensible are shown in Appendix IV.

Table 48. Average sensitivities of annual net recharge estimates to several input parameters of the model for Salinas's area for given increase in 10 percent.

Parameter	**Sensitivity**
PRASA	-8.4
AMC 3 NI	-5.2
Kc I	-5.0
PREPA	-4.4
Kc NI	-2.3
I perc	2.2
θ	-1.8
I area	-1.7
Eff. R I	-1.3
AMC 2 NI	-1.1

Given that groundwater pumpage so large compared to estimated percolation in the Salinas area, it's easy to imagine the average annual net groundwater recharge to be more sensitive to changes in pumpage than to other factors. The sensitivity of the water budget model to groundwater pumpage was investigated by assessing the impact that changes in each of the pumping purposes these parameters would have on the estimates of average recharge and ground water pumpage rates. Ten percent increase in groundwater pumpage showed that the model is extremely sensitive to pumpage from PRASA (-8.4) and from PREPA (-4.4). For most of the years under study for the Salinas area, pumpage for irrigation purposes is higher than all other pumpage combined which might mislead to the conclusion that irrigation pumpage is the most important factor to annual net aquifer recharge. Contrary to other groundwater extractions that extract aquifer water for ever, irrigation water pumpage does produces from return flow to the aquifer which reduces its local sensitivity.

The soil surface process model has one parameter (antecedent soil moisture content, AMC, which is based on the curve number, CN) and two data inputs (daily precipitation, P, and evapotranspiration, ETc, based on crop coefficients, Kc). Infiltration, and therefore effective precipitation (P-RO), is a function of the curve number. A reduction in the curve number would increase infiltration and provide more water for effective precipitation. Inversely, a 10 percent increase in the curve number resulted in a decrease in average annual net recharge reflected in average sensitivities of –5.2 and -1.1 for AMC 3 NI and AMC 2 NI, respectively.

In absence of field studies to assess irrigation efficiency, for this study, irrigation efficiencies and irrigation water percolation were estimated based on data obtained from the various USDA Agricultural Census publications on irrigation systems in the area. Although irrigation efficiency and in consequence irrigation percolation values are expected to vary with time, a single time invariant value for each one was used for each of the irrigation modeling periods. The sensitivity analysis of the water budget model to irrigation percolation values assessed by increasing its value by 10 percent resulted in a 2.2 percent increase in the average annual net recharge rate for the study area.

Because of the limited availability of areal and temporally distributed crop acreage and land use/land cover distribution data for the study area, data was lumped into 4 municipalities having uniform crop evapotranspiration coefficients for both irrigated (Kc I) and non irrigated (Kc NI) areas for the periods prior and after the cease of sugarcane production and uniform effective root depth (Eff. R) and field capacity (θ) for the entire study period. Evapotranspiration is directly proportional to the assign crop coefficients. The lumping of irrigated areas and non irrigated areas is expected to have a greater influence on model results than other assumptions such as lumping of soil types. The depth of the effective rooting zone and the field capacity, which determine the size of the storage reservoir, are integral components of the daily crop soil moisture budgets. The sensitivity of the water budget model used in this study resulted in a 1.3 and 1.8 percent decrease in recharge for effective root depth and field capacity, respectively. These sensitivities are greater than 1, as expected, indicating that the water budget model is sensitive to the size of the water storage reservoir (which is a function of both field capacity and crop rooting depth).

In similar studies, Yu *et al*. (2000) cited by Brush *et al*. (2004) found that estimated runoff and evapotranspiration were more sensitive to distributed land use than to distributed soil type. Similarly, Brush *et al*. (2004), studying the sensitivity of a similar water balance model found that recharge estimates are a function of the surface water delivery data and to the irrigated area. Contrary to results from the sensitivity analysis performed here, Brush *et al*. (2004) found that in their study area recharge estimates in the water balance were not very sensitive to the curve number or to the crop rooting depth.

Irrigated area data is an extremely important input to the water budget model. However, much of the crop acreage data input to the model for this study was estimated. An increase in 10 percent of irrigated area produces a decrease in 1.7 percent in estimated annual net groundwater recharge. The increases in irrigated land resulted in groundwater pumpage rise for all water budget areas for all years and it was similar for the increase in CN, Kc and Eff. R. Recharge is largely a function of surface water delivery rates and irrigation efficiency values, which remain constant even as the crop acreage varies. Groundwater pumpage rates are estimated as a function of the residual crop water demand after using surface water deliveries, and thus are extremely sensitive to cropped acreage.

6. Conclusions and Recommendations

A water balance was developed for the Patillas-Salinas coastal watersheds which for the past 100 years have been subject to intensive agricultural practices. Emphasis was given to the area served by two irrigation canals and to the groundwater supply. The period from 1980 through 2010 was used to develop a model for understanding and predicting changes in aquifer piezometric levels that takes into account land use changes and changes in irrigation water supplies. This data can serve as input in the planning and management of the water resources in the area. Two main alternatives were proposed for reducing the probability of saltwater intrusion to the aquifer, the reduction of groundwater pumpage and improve aquifer recharge from irrigation water excess and/or runoff collections.

6.1 Conclusions

Actual evapotranspiration clearly decreased during the year 1994 for the Guayama weather station and during the year 1999 for the Aguirre weather station due to a change in the difference daily temperature (Max – Min) and a change in daily variability between this two. It is believed that this is the result of two possible factors: 1) a change in the time of the day where maximum and minimum temperature is measured, 2) a change in the instruments itself.

In general, the years 1980 and 86, 1994 and 95, and 2002 and 09 were the most critical years in terms of recharge from precipitation water and are characterized as dry years. The years with the higher precipitation recharge are generally associated with big rain storms, tropical storms and/or hurricanes, like it was the case for the years 1985, 1988 and 1998. On the other hand, years like 1984 and 2010 produced high percolation even with no big precipitation events occurred because these were wet years that counted with very high precipitation distributed year around.

Percolation from irrigation gradually decreases from the early 1980s to the mid 2000s as irrigation efficiency gradually increased during this period. The more clear changes in irrigation water recharge occurred in the Guayama and Salinas modeling areas where during the last three decades an aggressive change from furrow to drip and sprinkler irrigation occurred in comparison to the Arroyo and Patillas modeling areas. Recharge from irrigation water in the 2000s is mostly negligible in the Guayama area and low in the Arroyo, Patillas and Salinas modeling areas when comparing it to the early 1980s.

Recharge from precipitation is believed to be 11 percent in average although can reach up to 22 percent in wet years. The difference in percolation estimates from precipitation that recharges the aquifer when compared to previous studies strives in the fact that the water budget model created here, takes into consideration the soil moisture prior to each precipitation event when estimating precipitation water percolation and aquifer recharge. In the Salinas to Patillas study area it was found that between 10 and 40 percent of total precipitation recharge comes as direct result of irrigation practices or, in other words, that there is a considerable increment in overall recharge from precipitation to the aquifer because of irrigation practices, especially from furrow irrigation.

Based on water deliveries data by PREPA and irrigation efficiency estimates, it is considered that in furrow irrigated fields about 20 percent of the irrigation water applied actually recharged the aquifer, where other 10 to 40 percent of recharge attributed by other researchers is actually recharge from precipitation in irrigated fields. This is precipitation that would not have percolated if no irrigation was present. In the same way, it is theorized that none of the water imported for drip irrigation percolates and that in sprinkler irrigated fields only about 5% of the imported water percolates, where all other percolation come from the interaction with precipitation.

It is estimated that streams in the Salinas modeling area are the most appropriate to the aquifer providing a higher annual rate of recharge while the Patillas modeling area experiences the least appropriate aquifer recharge from streams due to the blockage generated by the Patillas Dam create to the two principal streams, Río Grande de Patillas and Río Marín.

Irrigation canals are very important source of groundwater recharge because of its continuous and safe input to groundwater. While recharge from irrigation, precipitation and streams varies from year to year, recharge from the irrigation canals is a constant factor which can be a significant source of groundwater recharge for years even during extreme drought as it was during the years of 1980 and 1995.

Estimated groundwater recharge from the two reservoirs within the study area was determined as insignificant when compared to any of the other recharge inputs.

The general order of importance for groundwater recharge inputs was estimated as precipitation, streams, canals, irrigation and dams. Although this is true for Guayama, Arroyo and Patillas, interestingly it was not for Salinas. While in the Arroyo, Guayama and Patillas modeling areas, precipitation represented the greater input for groundwater recharge; in the Salinas area was the stream percolation the most important input, and in few cases canal recharge was most important than precipitation.

All four modeling areas experienced a reduction in groundwater pumpage after the sugarcane production stopped in the area due to the reduction in irrigation water requirement and in irrigated area. The greatest reduction in groundwater pumpage between the prior and after sugarcane production was experienced by Arroyo (49 %) while Guayama experienced the least changes (11 %). Reduction in groundwater pumpage in Patillas and Salinas was estimated to be 27 and 14 percent, respectively.

In general, results from the model show a very good aquifer in the Arroyo, Patillas and Guayama modeling areas in terms that net recharge occurred the vast majority of the years with average net recharge rates grater than 180 mm/yr. For these modeling areas, groundwater depletion that might have resulted in seawater intrusion only occurred during the year 1980 due to the high groundwater extractions for irrigation purposes in a dry year that counted with below average recharge. Arroyo and Guayama, respectively, experienced 18 and 24 percent decrease in net groundwater recharge between the periods prior and after the ending of sugarcane production in 1993 as direct result from the furrow irrigation sudden depletion. Although the Patillas area also experienced similar decrease in net groundwater recharge from irrigation practices after the year 1993 as Arroyo and Guayama did, Patillas actually experienced an increase of 25 percent in net groundwater recharge after the sugarcane termination. This is because in Patillas the termination of the sugarcane production represented an increase in flow from the Patillas reservoir, flow that before was used to go through the irrigation canals. This greater outflow from the Patillas reservoir in great part was used for aquifer recharge in the Patillas coastal plane.

On the other hand, results form the model show a poor condition South Coast aquifer in the Salinas area. According to the developed model results, in the Salinas area, groundwater depletion to the point of possible saltwater intrusion occurred during the years 1980, 1983, 1991, 1993, 1994, 1995, 1997, 2000, 2001, 2002, and 2009 due to the high water extractions for public supply and for irrigation practices. Contrary to the Arroyo, Guayama and Patillas modeling areas, in Salinas the average net groundwater recharge did not change between irrigation periods (prior and after sugarcane termination). This is because of a combination of factors: 1) groundwater pumpage in Salinas was kept fairly high because irrigation water pumpage was not greatly depleted after the ending of sugarcane production as the surface water imports did, 2) during the study period the major contributor to groundwater recharge in Salinas were the streams that during the 2000 to 2010 decade, in average, recharge from streams was 18 percent higher than in the previous two decades, which in proportion have compensated for the 92 percent losses in irrigation percolation.

Although the model was not meant to estimate groundwater levels, its estimated monthly net recharge followed the recharge trend explicitly represented by the groundwater levels obtained as piezometric elevation from the USGS Groundwater Watch: Puerto Rico Active Water Level Network. Positive net recharge in a monthly basis reduced or stopped the depletion in piezometric elevation in a standard basis or increased the piezometric elevation in the case of big precipitation events in the Salinas and Guayama area where it was evaluated.

Typically, net recharge is low or negative during the first quarter of the year. Recharge gradually increases during the second quarter of the year from April through July, drops in August (due to a distinctive reduction in precipitation during this month) to then greatly increase in September and October where it reaches its peak, to then drop in November and December.

The Salinas modeling area experienced the most critical scenario in terms of groundwater net recharge along the eastern part of the South Coast Aquifer. Stream base flow; which was estimated to be the main source of groundwater recharge in Salinas during the most recent decade, was dependent on the precipitation on the Río Majada basin which varies from year to year. Groundwater recharge from the Patillas-Guamaní irrigation canals, constituting about 10 percent of the total recharge to the aquifer in the Salinas area, represented a solid and constant source that maintains the aquifer health.

Because out of the four sources of groundwater recharge in the Salinas area, the Patillas-Guamaní irrigation canals are believed to be the most constant and secure source of water, two scenarios were studied as possible strategies for groundwater management in the area involving these irrigation canals assuming that its development is feasible. These alternatives are: 1) increase surface water imports from the canals to farms and decrease or eliminate groundwater extractions for irrigation practices, 2) create infiltration ponds that uses collected runoff and exceeding water from irrigation canal as source of aquifer recharge in strategic areas. Modeling of both alternatives presented a set of possible sources of input for groundwater recharge under the assumed conditions. During the study period, the worst case scenario in terms precipitation distribution and groundwater recharge is represented by the year 1995 in the Salinas area. This year is considered to be worst case scenario in terms of groundwater pumpage, when the aquifer would suffer greater stress. If no irrigation water pumpage was to occur during this year (where the estimated irrigation water requirement under today's conditions is estimated to be 1,555 mm) the irrigation canals would be able to provide 74 percent of the irrigation water requirement. On the other hand, it was found that the use of 2 shallow infiltration ponds of a total volume of 12,335 m^3 that are constantly feeding the aquifer with percolated water produce positive net groundwater recharge even in the worst case scenarios and could increase the average net recharge from 64 to 236 mm/year. These increase in three and a half times the average net groundwater recharge.

The sensitivity analysis for the water budget model showed that the groundwater pumpage, curve number, evapotranspiration coefficients, percolation from irrigation practices, soil maximum available water or field capacity , irrigated area and crop effective root depth could be the most sensible factors. Out of these parameters ground water pumpage from the Puerto Rico Aqueduct and Sewer Agency (PRASA) and the antecedent moisture content for normal conditions on non irrigated areas produced the greater and lesser variations to the model output, respectively.

6.1 Recommendations

1. A change in the difference daily temperature (Max – Min) was detected after the year 1994 in the Guayama weather station and after the year 1998 in the Aguirre weather station. Although this could have happened because of a change in the time of the day where maximum and minimum temperature is measured or a change in the instruments itself, this could also be the product of a change in the environment in the area. Further research in the subject is recommended.

2. Although recharge within the study area has been typically linked to annual precipitation, it is believed that recharge is as dependant on annual precipitation distribution as it is for annual total precipitation. Further research in the subject is recommended.

3. The feasibility of developing the currently abandoned agricultural land back into productive agriculture under furrow irrigation should be evaluated as an alternative to groundwater recharge and in aquifer management.

4. Field studies that quantify the amount of precipitation water that percolates as direct result of the interaction between irrigation and precipitation water in the soil for the different irrigation systems and irrigation management practices are recommended.

5. Field studies that quantify the amount of irrigation water that percolates through the soil for the different irrigation systems and irrigation management practices are recommended.

6. Actual recharge from reservoirs may vary from the presented estimates and further research on the subject is recommended.

7. Groundwater pumpage adjustment for dry years is recommended for future work and model improvement.

8. A study on the feasibility of using water from the Carite and Patillas Reservoirs as source of artificial groundwater recharge.

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Appendix I: Runoff modeling assessment

For assessment purposes, estimated runoff using the SCS CN model in a monthly basis was compared to monthly results from the four gage stations with substantial available data within the study area. This are: Río Grande de Patillas Above Dam, Río Marín in Patillas, and Río Majada and Río Lapa in Salinas.

Table A.1. Results from three years of SCS CN Runoff vs Measured Runoff for the Río Grande de Patillas Above Dam watershed using precipitation from Jájome Alto weather station.

2005	Measured	SCS CN	Precip.	Residuals	Residuals^2
	mm/mo	mm/mo	mm/mo	mm/mo	(mm/mo)^2
Jan	9.29	0.00	143.51	9.29	86.24
Feb	1.84	0.00	41.90	1.84	3.38
Mar	1.54	0.00	6.34	1.54	2.37
Apr	5.68	0.00	86.10	5.68	32.32
May	61.27	96.30	291.85	-35.03	1,226.79
Jun	71.92	3.38	177.55	68.54	4,697.06
Jul	156.42	65.87	302.50	90.55	8,199.37
Aug	47.48	0.23	153.41	47.25	2,232.33
Sep	20.68	0.00	38.86	20.68	427.69
Oct	427.80	157.82	521.20	269.98	7,2889.63
Nov	40.77	354.83	634.74	-314.05	98,629.56
Dec	2.56	37.32	228.09	-34.76	1,208.23
SUM	847.26	715.75	2,626.05	131.50	189,634.97

2006	Measured	SCS CN	Precip.	Residuals	Residuals^2
	mm/mo	mm/mo	mm/mo	mm/mo	(mm/mo)^2
Jan	36.34	10.29	141.22	26.05	678.74
Feb	8.35	0.00	68.34	8.35	69.71
Mar	11.00	8.59	147.56	2.41	5.80
Apr	19.47	14.20	135.62	5.27	27.78
May	6.85	0.21	88.90	6.64	44.05
Jun	92.80	33.54	280.15	59.27	3,512.45
Jul	174.47	46.77	283.99	127.70	16,306.90
Aug	42.85	104.85	274.83	-61.99	3,842.98
Sep	5.92	0.00	30.22	5.92	35.06
Oct	138.01	36.26	278.89	101.75	10,352.44
Nov	12.36	0.00	96.52	12.36	152.89
Dec	9.13	0.00	125.46	9.13	83.39
SUM	557.57	254.72	1,951.70	302.85	35,112.19

2007	Measured	SCS CN	Precip.	Residuals	Residuals^2
	mm/mo	**mm/mo**	**mm/mo**	**mm/mo**	**(mm/mo)^2**
Jan	1.83	0.00	44.45	1.83	3.36
Feb	5.01	0.00	37.58	5.01	25.09
Mar	7.02	0.00	65.77	7.02	49.29
Apr	12.30	0.70	108.96	11.60	134.53
May	6.15	0.00	84.84	6.15	37.80
Jun	7.19	0.00	76.22	7.19	51.68
Jul	26.27	0.00	57.16	26.27	689.87
Aug	48.55	88.82	301.76	-40.27	1,621.48
Sep	22.11	0.37	109.48	21.74	472.54
Oct	243.76	360.63	680.72	-116.88	13,660.51
Nov	2.55	34.12	171.71	-31.57	996.56
Dec	60.60	76.10	258.57	-15.50	240.23
SUM	443.33	560.74	1,997.22	-117.41	17,982.94

Table A.2. Results from three years of SCS CN Runoff vs Measured Runoff for the Río Marin watershed using precipitation from Jájome Alto weather station.

2005	Measured	SCS CN	Precip.	Residuals	Residuals^2
	mm/mo	**mm/mo**	**mm/mo**	**mm/mo**	**(mm/mo)^2**
Jan	4.97	0.00	143.51	4.97	24.74
Feb	3.21	0.00	41.90	3.21	10.30
Mar	1.67	0.00	6.34	1.67	2.81
Apr	3.36	0.00	86.10	3.36	11.29
May	37.66	101.76	291.85	-64.11	4,109.60
Jun	58.34	4.04	177.55	54.30	2,948.77
Jul	81.73	68.60	302.50	13.13	172.35
Aug	37.98	0.48	153.41	37.50	1,406.26
Sep	6.04	0.00	38.86	6.04	36.42
Oct	357.03	166.36	521.20	190.66	36,352.58
Nov	62.31	361.56	634.74	-299.25	89,550.57
Dec	7.77	40.41	228.09	-32.64	1,065.42
SUM	662.07	743.22	2,626.05	-81.15	135,691.11

2006	**Measured**	**SCS CN**	**Precip.**	**Residuals**	**Residuals^2**
	mm/mo	**mm/mo**	**mm/mo**	**mm/mo**	**(mm/mo)^2**
Jan	33.09	24.90	218.69	8.20	67.16
Feb	5.94	0.00	68.34	5.94	35.30
Mar	4.83	9.78	147.05	-4.95	24.47
Apr	4.96	16.33	136.13	-11.37	129.26
May	15.13	0.42	88.90	14.71	216.38
Jun	83.08	35.66	276.85	47.41	2,247.92
Jul	110.38	49.91	287.29	60.46	3,655.79
Aug	45.28	106.09	265.94	-60.80	3,697.14
Sep	11.05	0.00	39.11	11.05	122.13
Oct	72.33	38.19	273.81	34.14	1,165.43
Nov	27.86	0.00	101.60	27.86	776.25
Dec	26.70	0.00	119.62	26.70	712.89
SUM	440.64	281.29	2,023.33	159.35	12,850.12

2007	**Measured**	**SCS CN**	**Precip.**	**Residuals**	**Residuals^2**
	mm/mo	**mm/mo**	**mm/mo**	**mm/mo**	**(mm/mo)^2**
Jan	6.46	0.00	44.45	6.46	41.70
Feb	5.01	0.00	37.58	5.01	25.12
Mar	9.38	0.00	65.77	9.38	87.95
Apr	11.56	1.13	108.96	10.44	108.97
May	11.20	0.00	84.84	11.20	125.48
Jun	11.92	0.00	76.22	11.92	141.97
Jul	21.29	0.00	57.16	21.29	453.14
Aug	74.18	91.64	301.76	-17.46	305.00
Sep	27.11	0.70	109.48	26.42	697.78
Oct	202.80	364.24	680.72	-161.44	26,064.48
Nov	5.74	35.72	171.71	-29.98	898.65
Dec	63.32	78.51	258.57	-15.19	230.69
SUM	449.97	571.93	1,997.22	-121.97	29,180.92

Table A.3. Selected years of SCS CN Runoff vs Measured Runoff for the Río Majada watershed using precipitation from Aibonito weather station.

2005	**Measured**	**SCS CN**	**Precip.**	**Residuals**	**Residuals^2**
	mm/mo	**mm/mo**	**mm/mo**	**mm/mo**	**(mm/mo)^2**
Jan	1.52	0.00	143.51	1.52	2.30
Feb	0.57	0.00	41.90	0.57	0.33
Mar	0.52	0.00	6.34	0.52	0.27
Apr	1.23	0.00	86.10	1.23	1.50
May	16.69	58.51	291.85	-41.82	1,749.00
Jun	4.70	0.26	177.55	4.44	19.74
Jul	31.41	34.36	302.50	-2.95	8.71
Aug	2.08	0.00	153.41	2.08	4.33
Sep	7.89	0.00	38.86	7.89	62.19
Oct	148.58	87.40	521.20	61.18	3,742.99
Nov	1.11	279.83	634.74	-278.71	77,680.26
Dec	1.57	15.80	228.09	-14.22	202.35
SUM	217.88	476.16	2,626.05	-258.28	83,473.98

2006	**Measured**	**SCS CN**	**Precip.**	**Residuals**	**Residuals^2**
	mm/mo	**mm/mo**	**mm/mo**	**mm/mo**	**(mm/mo)^2**
Jan	1.72	5.02	141.22	-3.29	10.85
Feb	0.58	0.00	68.34	0.58	0.33
Mar	3.70	2.36	147.56	1.34	1.78
Apr	6.18	4.40	135.62	1.78	3.18
May	0.70	0.00	88.90	0.70	0.49
Jun	7.09	12.85	280.15	-5.75	33.10
Jul	11.93	16.54	283.99	-4.61	21.27
Aug	16.48	69.49	274.83	-53.01	2,810.00
Sep	1.71	0.00	30.22	1.71	2.93
Oct	9.15	16.04	278.89	-6.89	47.43
Nov	2.46	0.00	96.52	2.46	6.07
Dec	0.89	0.00	125.46	0.89	0.79
SUM	62.59	126.69	1,951.70	-64.10	2,938.22

2007	Measured	SCS CN	Precip.	Residuals	Residuals^2
	mm/mo	mm/mo	mm/mo	mm/mo	(mm/mo)^2
Jan	0.33	0.00	44.45	0.33	0.11
Feb	0.29	0.00	37.58	0.29	0.09
Mar	0.28	0.00	65.77	0.28	0.08
Apr	1.10	0.00	108.96	1.10	1.21
May	0.65	0.00	84.84	0.65	0.43
Jun	0.42	0.00	76.22	0.42	0.18
Jul	0.11	0.00	57.16	0.11	0.01
Aug	2.54	56.74	301.76	-54.20	2,937.19
Sep	0.54	0.00	109.48	0.54	0.30
Oct	78.63	271.40	680.72	-192.76	37,158.24
Nov	1.05	18.59	171.71	-17.55	307.83
Dec	16.35	48.41	258.57	-32.06	1,027.64
SUM	102.32	395.14	1,997.22	-292.82	41,433.30

Table A.4. Results from three years of SCS CN Runoff vs Measured Runoff for the Río Lapa watershed using precipitation from Jájome Alto weather station.

2005	Measured	SCS CN	Precip.	Residuals	Residuals^2
	mm/mo	mm/mo	mm/mo	mm/mo	(mm/mo)^2
Jan	3.83	0.00	143.51	3.83	14.70
Feb	0.14	0.00	41.90	0.14	0.02
Mar	0.27	0.00	6.34	0.27	0.07
Apr	0.73	0.00	86.10	0.73	0.53
May	7.46	47.54	291.85	-40.08	1,606.79
Jun	1.34	0.08	177.55	1.26	1.59
Jul	22.65	27.97	302.50	-5.32	28.29
Aug	2.93	0.00	153.41	2.93	8.56
Sep	4.90	0.00	38.86	4.90	23.98
Oct	103.06	69.94	521.20	33.12	1,097.07
Nov	2.75	259.48	634.74	-256.73	65,912.20
Dec	0.25	10.77	228.09	-10.52	110.68
SUM	150.31	415.79	2,626.05	-265.48	68,804.48

2006	Measured	SCS CN	Precip.	Residuals	Residuals^2
	mm/mo	mm/mo	mm/mo	mm/mo	(mm/mo)^2
Jan	1.34	5.55	218.69	-4.21	17.70
Feb	0.72	0.00	68.34	0.72	0.52
Mar	7.53	1.51	147.05	6.02	36.27
Apr	13.66	2.29	136.13	11.37	129.39
May	0.98	0.00	88.90	0.98	0.96
Jun	2.42	8.83	276.85	-6.42	41.17
Jul	3.86	11.39	287.29	-7.53	56.73
Aug	6.55	61.07	265.94	-54.52	2,972.69
Sep	10.60	0.00	39.11	10.60	112.32
Oct	2.97	11.62	273.81	-8.66	74.98
Nov	0.98	0.00	101.60	0.98	0.95
Dec	0.32	0.00	119.62	0.32	0.11
SUM	51.92	102.26	2,023.33	-50.34	3,443.79

2007	Measured	SCS CN	Precip.	Residuals	Residuals^2
	mm/mo	mm/mo	mm/mo	mm/mo	(mm/mo)^2
Jan	0.41	0.00	44.45	0.41	0.16
Feb	0.57	0.00	37.58	0.57	0.32
Mar	0.61	0.00	65.77	0.61	0.37
Apr	0.75	0.00	108.96	0.75	0.57
May	0.20	0.00	84.84	0.20	0.04
Jun	0.15	0.00	76.22	0.15	0.02
Jul	0.07	0.00	57.16	0.07	0.00
Aug	1.29	48.44	301.76	-47.15	2,223.58
Sep	0.16	0.00	109.48	0.16	0.03
Oct	80.19	247.05	680.72	-166.86	27,841.09
Nov	0.88	15.51	171.71	-14.63	214.08
Dec	20.76	42.32	258.57	-21.57	465.07
SUM	106.05	353.33	1,997.22	-247.29	30,745.34

Appendix II: Evapotranspiration Calibration and Validation

Evapotranspiration Calibration

The Food and Agriculture Organization (FAO) recommends the Penman-Monteith model as the sole method to be used for estimating evapotranspiration (ET) (Smith *et al*. 1996). This method depends on net radiation, soil heat flux, air temperature, humidity and wind speed. Unfortunately, the intensive data requirements needed to estimate ET with this method have made the Penman-Monteith model almost unusable for farmers in Puerto Rico. On the island, there are only about seven pyronometers to measure solar or shortwave radiation (R_s) and about the same amount of weather stations with enough data for the Penman-Monteith method to be used. However, over the last few years a body of work has began to be develop in Puerto Rico for the use of the Penman Monteith model. Harmsen *et. al.* (2001) compared consumptive water use estimates for pumpkin and onion for the SCS Blaney-Criddle and Penman-Monteith methods at two locations in Puerto Rico. Harmsen *et al*. (2002) developed a procedure for estimating climate parameters in Puerto Rico which are needed for input to the Penman-Monteith reference evapotranspiration (ET_0) equation. Harmsen's version of the Penman-Monteith model only requires site latitude, elevation and the NOAA Climate Division number. Recently a number of papers in Puerto Rico have been published using the Penman-Monteith method (Harmsen *et al*., 2008, Ramirez-Builes, 2007, Ramirez-Builes *et al*., 2008, Ramirez-Builes *et al*., 2006, Harmsen *et al*., 2006).

Allen *et al.* (1998) recommends the Hargreaves Samani model (Equation 10) to be used for estimating ET_0 when there is not enough data to use the Penman-Monteith model. He recommends that the Hargreaves Samani model be verified in each new region by comparing it with estimates by the FAO Penman Monteith equation at nearby weather stations where solar radiation, air temperature, humidity, and wind speed are measured. Allen *et al*. (1998) recommends performing monthly or yearly calibration/validations. Eric Harmsen (Biosystems engineering Professor at University of Puerto Rico at Mayagüez, personal communication, 2011) has compared the Penman-

Monteith and the Hargreaves-Samani models for each of the six NOAA Climate Divisions Areas in Puerto Rico with reliable results.

The Generalized Penman-Monteith Method is given as follows (Allen *et al*., 1998):

$$ET = \frac{\Delta \cdot (R_n - G) + \rho_a \cdot c_p \cdot \frac{(e_s - e_a)}{r_a}}{\lambda \cdot \left[\Delta + \gamma \cdot \left(1 + \frac{r_s}{r_a} \right) \right]} \qquad A1$$

where Δ is slope of the vapor pressure curve (kPa/°C), R_n is net radiation (MJ/m^2-day), G is soil heat flux density (MJ/m^2-day), ρ_a is air density (kg/m^3), c_p is specific heat of air (MJ/kg-°C), γ is psychometric constant (kPa/°C), T is the air temperature at two meters high (°C), u_2 is wind speed at two meters elevation (m/s), e_s is the saturated vapor pressure (kPa), e_a is the actual vapor pressure (kPa), r_a is the aerodynamic resistance (s/m) and r_s is bulk surface resistance (s/m). The value of the aerodynamic resistance can be estimated with a theoretical equation (Allen *et al*., 1998):

$$r_a = \frac{\ln\left[\frac{(z_m - d)}{z_{om}}\right] \cdot \ln\left[\frac{(z_h - d)}{z_{oh}}\right]}{k^2 \cdot u_2} \qquad A2$$

where z_m is height of wind measurement (m), z_h is height of humidity measurement (m), d is the zero plane displacement height equal to 0.67 h, h is crop height (m), z_{om} is roughness length governing momentum transfer equal to 0.123 h, z_{oh} is roughness length governing transfer of heat and vapor equal to 0.1 z_{om}, and k is von Karman's constant (0.41). Allen et al. (1998) reported that the r_a equation and the associated estimates of d, z_{om} and z_{oh} are applicable for a wide range of crops. This model is restricted to neutral stability conditions, i.e. where temperature, atmospheric pressure, and wind velocity distribution follow nearly adiabatic conditions (no heat exchange).

To simplify the computational aspects of both ET_0 models, the Allen (1998) REF-ET spreadsheet was used to estimate daily ET_0 by using the FAO 56 Penman Monteith and the Hargreaves Samani models. In addition, the Hargreaves Samani model was computed using both the measured daily solar radiation (R_s) and average extraterrestrial radiation (R_a) to assess the reliability of estimating ET_0 based on measured solar radiation (R_s) versus average daily extraterrestrial radiation (R_a). For reliability verification purposes, the three ET_0 estimates then were translated into monthly estimates by adding its daily values and plotting them against the Penman Monteith model.

There is a USDA Natural Resources Conservation Service (NRCS) Soil Climate Analysis Network (SCAN) weather station located in the Fortuna Federal Experimental Station in Juana Díaz. This weather station is located around 40 kilometers west of the center of the Salinas to Patillas study area. It is the closest weather station with all the required data for the Penman-Monteith model. Due to its proximity, similar climate, and been located over the South Coast Aquifer this weather station was used to evaluate the accuracy of the Hargreaves-Samani model in relation to the Penman-Monteith. As recommended by Allen *et al*. (1998), the Hargreaves-Samani model was evaluated by estimating ET_0 from both solar radiation approaches (R_a and R_s), and from both models (Hargreaves-Samani and Penman-Monteith) on a monthly basis for the 2007, 2008 and 2009 calendar years.

The results showed an excellent correlation between Hargreaves Samani ET_0 estimates based on R_a compared to estimates from R_s (Figure A.1 and Table A.5). For the 3 year period, monthly comparison of Hargreaves-Samani based ET_0 between both solar radiation data (R_a vs R_s) has shown to be extremely similar where the differences or errors ranged between -1.56 and 2.78 mm/mo with an average of 0.13 mm/mo and a standard deviation of 1.16 mm/mo.

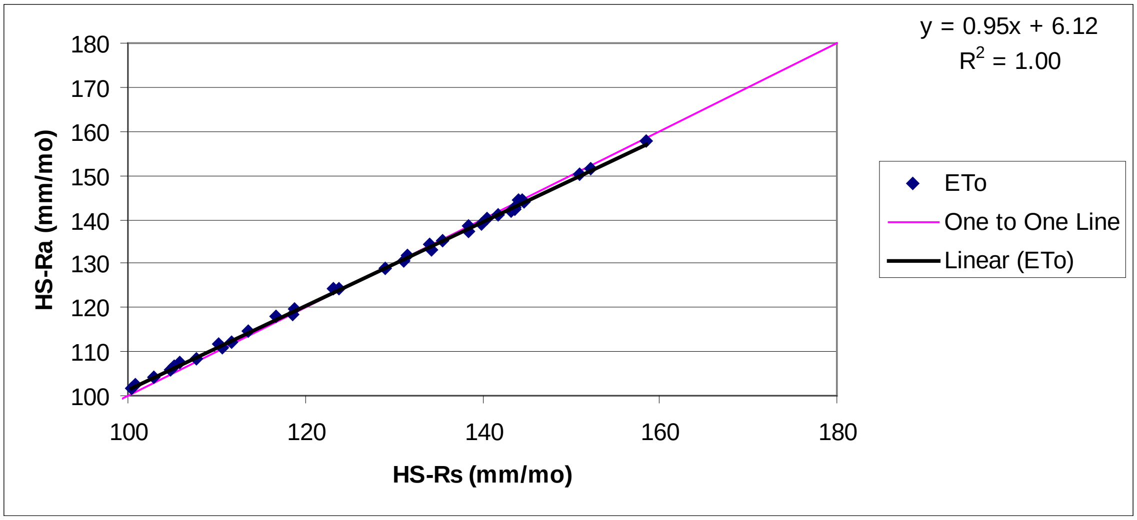

Figure A.1. Hargreaves Samani from measured solar radiation (Rs) vs Hargreaves Samani from average extraterrestrial radiation (Ra).

Table A.5. Monthly differences of Hargreaves-Samani ET_0 based on R_a vs R_s data for Fortuna weather station (mm/mo).

Max	2.78
Min	-1.56
Mean	0.13
STD	1.16

On the other hand, monthly comparison between the R_a based Hargreaves-Samani and the Penman-Monteith methods for the given 3 year period resulted in non significant differences (Figure A.2) although calibration is required. The monthly differences between these two methods were in the range between -11.70 and 22.16 mm/mo with an average difference of 4.11 mm/mo and a standard deviation of 6.96 mm/mo.

Considering that better results could be obtained (Figure A.3 and Table A.6), a slight calibration was performed by changing the model's empirical adjustment from 0.0023 to 0.00237 in the Hargreaves Samani equation. This calibration resulted in errors between -17.82 and 17.61 mm/mo with an average difference of 0.08 mm/mo and a standard deviation of 7.15 mm/mo, also in a slightly smaller sum of squared errors. More importantly, plotting the Penman Monteith against the Calibrated Hargreaves Samani, a better distribution of points below and above a one to one lines was obtained.

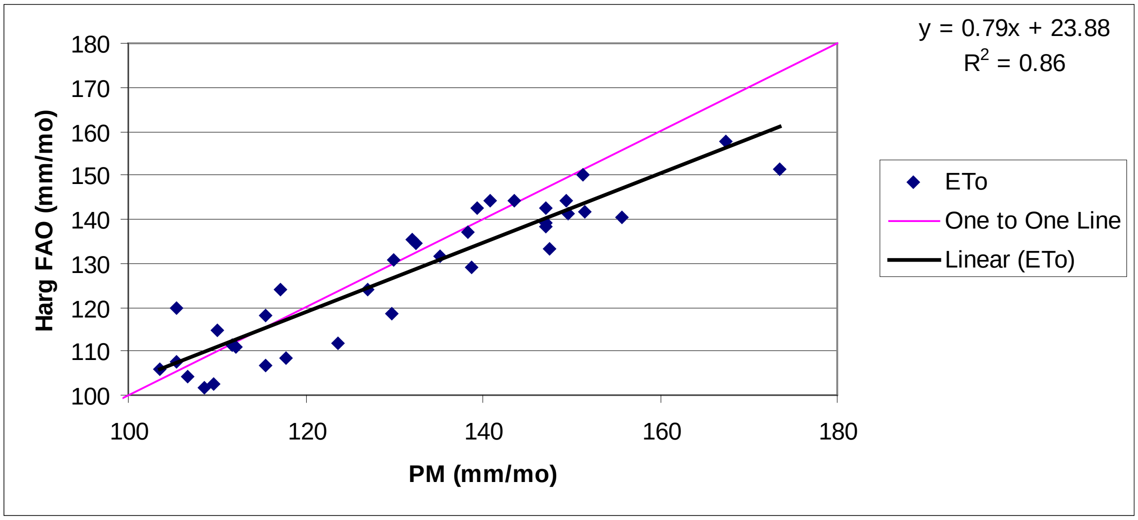

Figure A.2. Penman Monteith vs Hargreaves Samani.

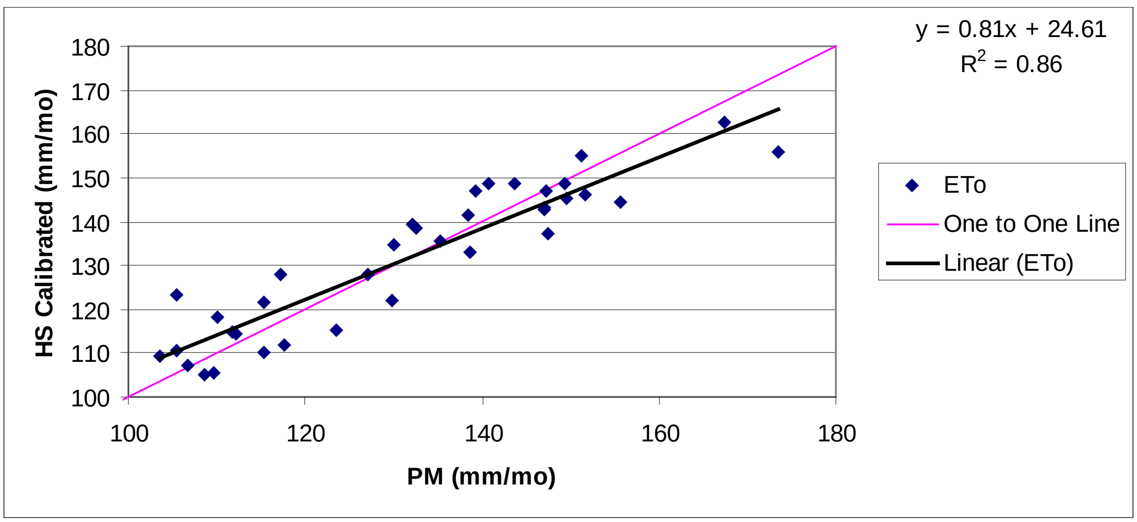

Figure A.3. Penman Monteith vs Calibrated Hargreaves Samani.

Table A.6. Monthly comparison between the R_s based Hargreaves-Samani and the Penman-Monteith methods for the given 3 year period.

	Hargreaves-Samani	Calibrated Hargreaves-Samani
Max	22.16	17.61
Min	-11.70	-17.82
Mean	4.11	0.08
STD	6.96	7.15

A yearly based residual analysis confirmed the reliability of the calibration (Table A.7). The sum of residuals between the Penman-Monteith and the Hargreaves-Samani model for the years 2007, 2008 and 2009 resulted in 11.49, 5.81 and 81.23 mm/yr, which means that the Hargreaves-Samani model under estimated ET_0 by this amount each year. Calibrated results (Table A.7) showed a better distribution of the sum of residuals, -37.93 mm for the year 2007, 6.27mm for the year 2008 and 32.37 for the year 2009. This indicates that for the year 2007 the Hargreaves Samani model over estimated ET_0 value was -37.93 mm for the total Penman Monteith estimated evapotranspiration for that year and, in the same way, during the years 2008 and 2009 the Hargreaves Samani Method over estimated the annual ET_0 by 6.27mm and 32.7mm, respectively.

Table A.7. Yearly based residual analysis of the data.

	Hargreaves-Samani		Calibrated Hargreaves-Samani	
	Σ Residuals	Σ Residuals^2	Σ Residuals	Σ Residuals^2
2007	11.49	169.23	-37.93	174.59
2008	55.81	222.43	6.32	215.27
2009	81.23	214.98	32.37	200.67
Total	148.64	606.63	1.00	590.48

Even though the Hargreaves Samani method utilizes only two climatic factors, extraterrestrial radiation and temperature, it presents reliable ET_0 estimates and surely can be use to estimate ET_0 in the Salinas to Patillas area given that there is not sufficient data to calculate by using the Penman Monteith method. ET_0 might be over and under estimated on days where there is great weather variability, but this can become insignificant over a long period of time.

Evapotranspiration Validation

Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open water surface. Although the pan responds in a similar fashion to the same climatic factors affecting crop transpiration, several factors produce significant differences in loss of water from a water surface and from a cropped surface (Allen *et al*., 1998). Not withstanding the difference between pan-evaporation and the evapotranspiration of cropped surfaces, the use of pans to predict ET_0 for periods of 10 days or longer may be warranted (Allen *et al*., 1998). Pan evaporation is related to the ET_0 by an empirically derived pan coefficient:

$$ET_0 = K_p * E_{pan} \qquad \text{A3}$$

where ET_0 is the reference evapotranspiration [mm/day], K_p is the pan coefficient, and E_{pan} is the measured pan evaporation [mm/day].

Allen *et. al.* (1998) presented an empirical equation to calculate the pan coefficient:

$$K_p = 0.108 - 0.0286u_2 + 0.0422\ln(FET) + 0.1434\ln(RH_{mean}) - 0.000631[\ln(FET)]^2 \ln(RH_{mean}) \quad \text{A4}$$

where K_p is the pan coefficient, u_2 is the average daily wind speed at two meters high (m/s), RH_{mean} is the average daily relative humidity (%), and FET is the fetch or distance of the identified surface type (grass or short green agricultural crop for case A, dry crop or bare soil for case B upwind of the evaporation pan). Preliminary sensitivity analysis of the use of this model to estimate K_p in Aguirre showed to be least sensible to FET, then to u_2, and more sensitive to RH_{mean}.

According to Harmsen and González (2002) the 30 year wind velocity (u_2) for the Aguirre area is 2 m/s and the relative humidity (RH_{mean}) is 77.3 %, while it is believed that the pan fetch area (FET) is about 35m. Substituting these values in pan evaporator equation we get a K_p value of 0.79. This K_p value is used to estimate the pan based ET_0. Allen et al (1998) states that this method is mostly useful for ET_0 estimates of ten days or longer.

The Aguirre weather station gathered pan evaporation data from 1970 to 1980 (CLIMOD). This 10 year period, even prior to the start date of this study, was used as long term validation for the calibrated Hargreaves Samani method be utilized to estimate ET_0 in the Salinas to Patillas area, assuming that long term pan evaporation is similar to long term ET_0 as inferred from Allen *et al*. (1998). During this period, days when either maximum or minimum temperature, or pan evaporation data was missing, were eliminated from the validation process to avoid biases. Also, daily pan evapotranspiration rates higher than 9.25 mm/day were eliminated assuming that evapotranspiration rates higher than 9.25 mm/day are not possible in the area. The highest evapotranspiration rate estimated using the Penman Monteith method during the year 2008 in the nearby Fortuna weather station was 7.74 mm/day. The elimination of these days of data translated to 283 days eliminated in the ten year data set.

For validation purposes, pan evaporation data and ET_0 estimates were lumped into periods of 23 days. The calibrated Hargreaves Samani model proved to be very accurate when compared to the pan evaporation data, having very low residuals on a 23 day comparison with an average residual of 0.56 mm/23 days, maximum of 29.69 mm/23 days, minimum of – 31.84 mm/23 days, and standard deviation of 12.09. In addition, the ten year period of daily ET_0 estimates based on pan evaporation resulted in a total of 14966 mm while during the same period the daily ET_0 estimates, based on the calibrated Hargreaves Samani method, resulted in 15045 mm, a difference of just 79 mm over a period of ten years or an error of 0.53%. This validates the use of the adjusted Hargreaves Samani method to estimate ET_0 in the Salinas to Patillas area. Figure A.4 presents the results of the validation process.

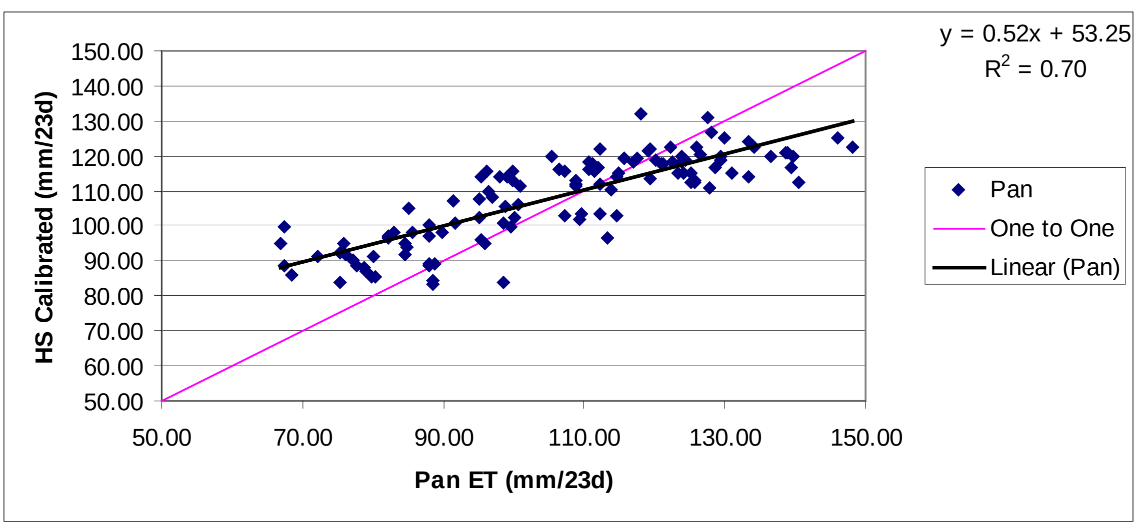

Figure A.4. Pan Evaporation vs Calibrated Hargreaves Samani.

Appendix III: Estimated Surface Water Deliveries Validation

Irrigation Water Deliveries Validation

Estimated monthly irrigation water deliveries by the Puerto Rico Electric and Power Authority (PREPA) per sub-modeling area were estimated based on linear regression analysis between irrigation water requirement and surface water deliveries. Results from this analysis in an annual basis are presented in the next 2 figures where the Irrigation Water Deliveries on Monthly Estimates (I adm) refers to the sum of monthly estimated water deliveries for a determined year for the four sub-modeling areas and Total Irrigation Water Deliveries by PREPA (I ad) refers to the actual water delivered by PREPA for irrigation within the study area.

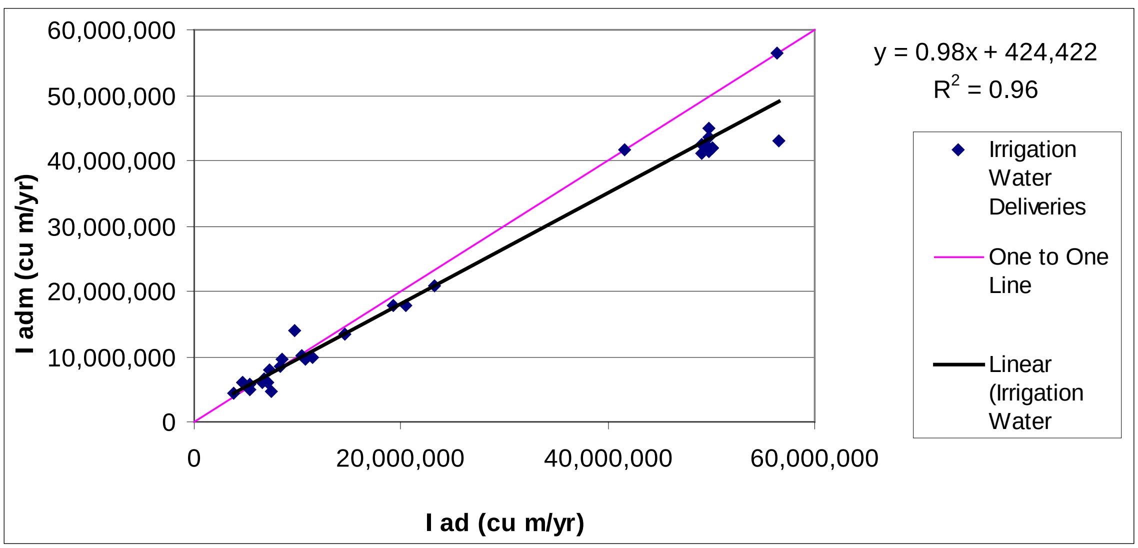

Figure A.5. Annual irrigation surface water deliveries (I ad) as compared to the sum of estimated annual surface water deliveries by sub-modeling area.

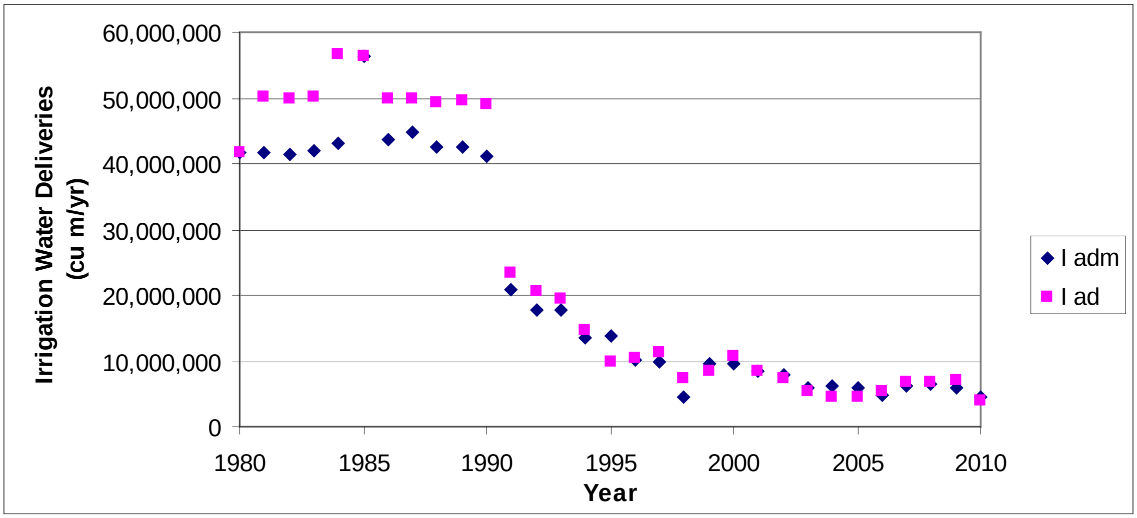

Figure A.6. Annual irrigation surface water deliveries (I ad) as compared to the sum of estimated annual surface water deliveries by sub-modeling area.

Appendix IV: Sensitivity Analysis

Table A.8. Sensitivity of the 10 factors considered most sensitive for the Salinas modeling area in an annual basis. Sensitivities are reported here as percent change in the average recharge rate in response to a 10 percent increase in the input parameter.

	Kc I	Kc NI	Eff. R I	θ	AMC 2 NI	AMC 3 NI	I area	I Perc	PRASA	PREPA
1980	3.10	0.02	0.30	0.41	0.16	0.00	1.68	-1.95	3.88	1.84
1981	-6.56	-0.97	-0.06	-0.85	-1.32	-3.95	-1.80	2.99	-7.22	-3.65
1982	-38.46	-3.07	-3.66	-6.27	-4.62	-9.04	-11.06	14.43	-39.31	-17.23
1983	23.74	4.28	-3.28	5.75	6.76	18.52	22.62	-33.58	60.23	24.35
1984	-2.75	-0.61	0.43	0.14	-0.69	-3.22	-0.98	1.75	-3.70	-1.49
1985	-2.93	-0.55	0.88	0.57	-0.12	-6.08	-1.32	2.07	-3.38	-1.20
1986	-8.13	-0.74	-2.35	-3.40	-0.89	-2.46	-3.16	4.16	-5.86	-4.26
1987	-0.95	-0.33	-0.05	-0.24	-0.08	-2.30	-0.51	0.77	-1.69	-0.89
1988	-2.52	-0.72	-0.89	-1.05	-0.42	-1.24	-1.13	1.58	-2.83	-1.45
1989	-6.36	-1.23	1.77	1.14	0.00	-7.60	-4.90	5.85	-12.25	-5.96
1990	-1.63	-0.34	0.26	0.14	-0.19	-3.56	-0.69	0.97	-2.27	-1.06
1991	3.32	0.76	1.09	1.62	0.00	2.04	2.06	-2.48	5.77	2.47
1992	-32.73	-4.65	-15.27	-17.53	0.00	-16.28	-18.30	24.15	-44.57	-21.42
1993	1.94	0.20	-0.82	-0.42	0.68	0.30	1.93	-2.24	4.40	1.90
1994	2.13	0.38	0.17	0.46	0.00	0.34	1.28	-1.52	4.72	2.03
1995	3.94	1.44	0.16	0.92	0.42	1.91	2.29	-2.50	12.22	5.27
1996	-2.39	-0.03	-0.14	-0.51	0.00	-0.68	-0.89	1.28	-5.85	-2.55
1997	5.03	0.74	-0.29	0.49	0.00	2.31	2.94	-3.51	13.69	5.42
1998	-0.77	-0.69	-0.01	-0.12	0.00	-1.97	-0.20	0.47	-1.62	-0.77
1999	-1.79	-1.05	0.48	0.15	-0.49	-4.81	-1.25	1.65	-4.84	-2.30
2000	15.44	2.43	-0.85	3.31	0.00	6.65	8.48	-10.58	30.24	14.35
2001	3.21	0.01	0.66	0.77	0.00	0.00	1.32	-1.72	3.84	1.82
2002	2.66	0.64	-0.72	-0.46	0.12	2.20	1.46	-1.88	3.66	1.80
2003	-2.06	-0.59	0.24	-0.22	-0.59	-2.29	-0.80	1.36	-3.20	-1.58
2004	-9.95	-0.84	0.46	-0.66	-1.70	-2.39	-5.14	6.68	-15.76	-7.76
2005	-1.46	-0.81	0.13	-0.19	-0.12	-2.22	-0.51	0.79	-2.25	-1.11
2006	-96.23	-61.87	-20.20	-37.57	-31.47	-121.60	-44.57	59.33	-241.64	-119.00
2007	-2.78	-1.66	0.19	-0.51	-0.40	2.31	-1.13	1.68	-9.83	-4.84
2008	-0.72	-0.61	0.24	0.02	0.00	-3.93	-0.47	0.64	-3.08	-1.51
2009	2.42	0.00	0.02	0.02	0.00	0.00	1.52	-1.78	9.12	4.49
2010	-0.37	-0.64	0.00	-0.26	-0.31	-1.84	-0.08	0.23	-1.44	-0.71
Average	-4.99	-2.29	-1.33	-1.75	-1.14	-5.19	-1.66	2.23	-8.41	-4.35
STD	20.19	11.16	4.57	7.59	5.85	22.30	10.08	13.62	46.73	22.66

Appendix V: Annual Irrigation Water Budget

Irrigation water budgets might be an important asset when planning use, distribution and general management of surface and groundwater in the Salinas to Patillas area. Here we present the estimated historical agricultural and irrigation water budgets for the past 31 years for each sub-modeling area are presented in the following figures.

Estimated Annual Irrigation Budget

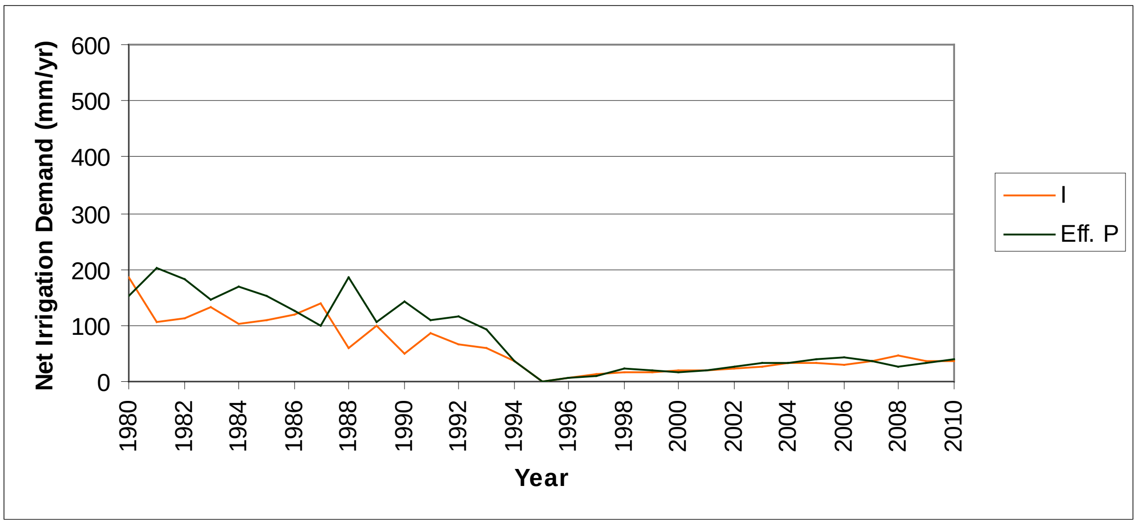

Figure A.7. Net irrigation water demand (I) and effective precipitation (Eff. P) for Arroyo modeling area

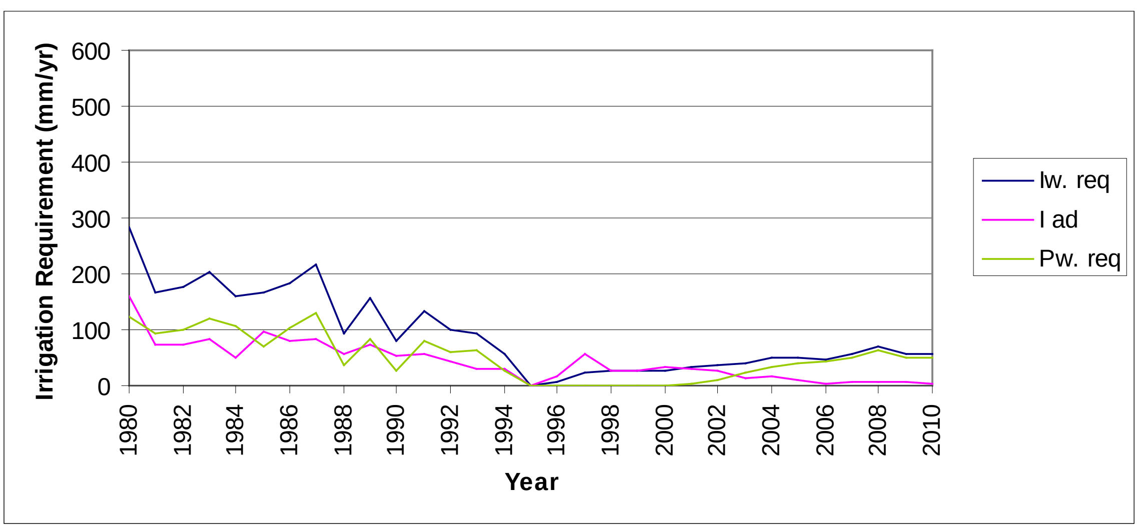

Figure A.8. Irrigation water requirement (Iw. req), imports (I ad) and extractions (Pw. req) for Arroyo modeling area

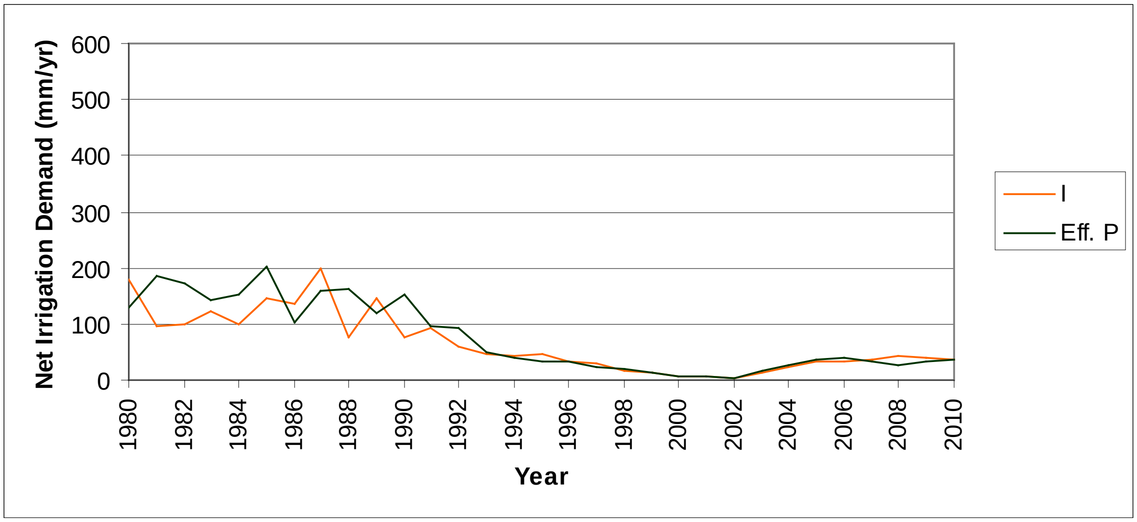

Figure A.9. Net irrigation water demand (I) and effective precipitation (Eff. P) for Guayama modeling area

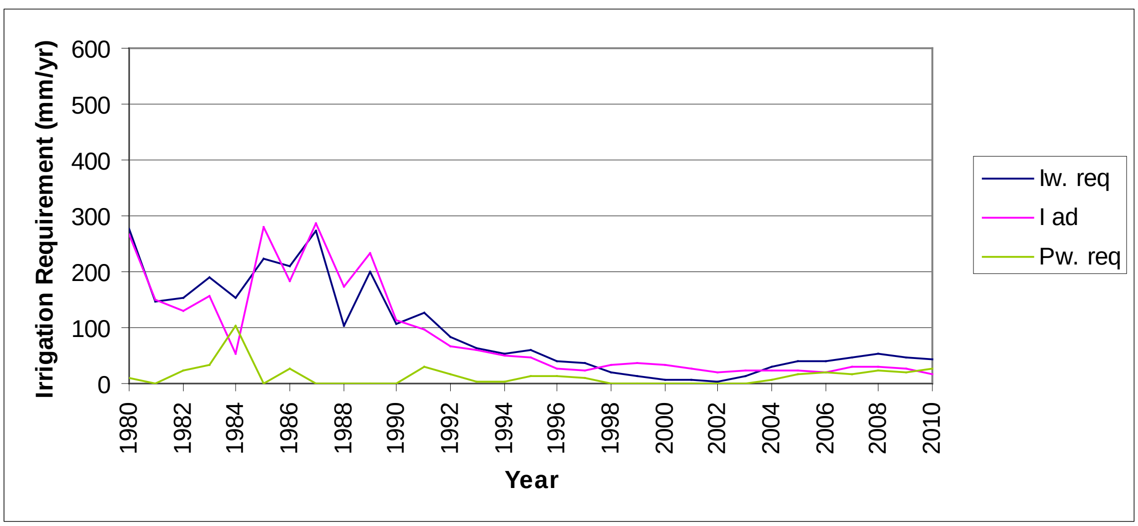

Figure A.10. Irrigation water requirement (Iw. req), imports (I ad) and extractions (Pw. req) for Guayama modeling area

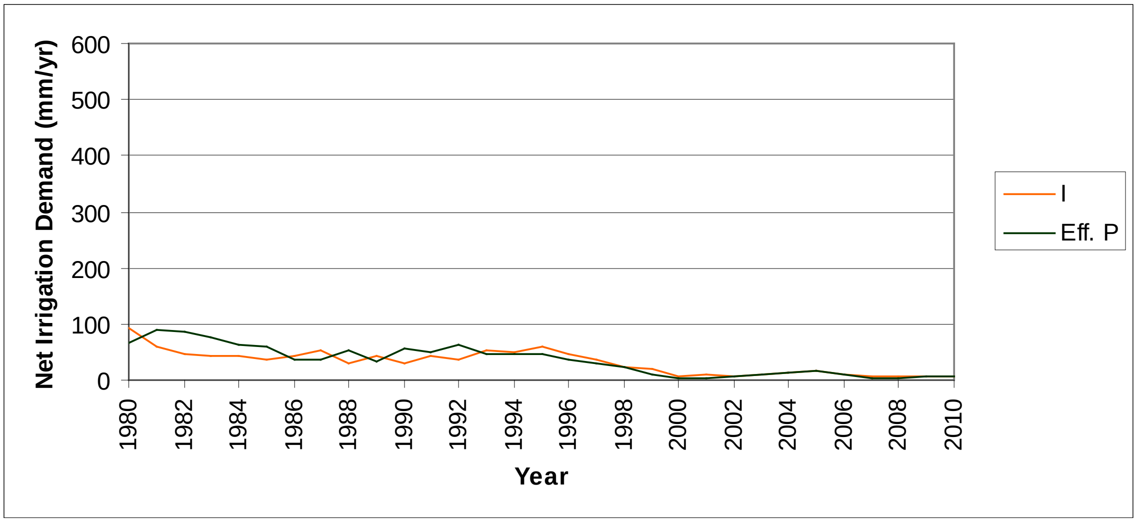

Figure A.11. Net irrigation water demand (I) and effective precipitation (Eff. P) for Patillas modeling area

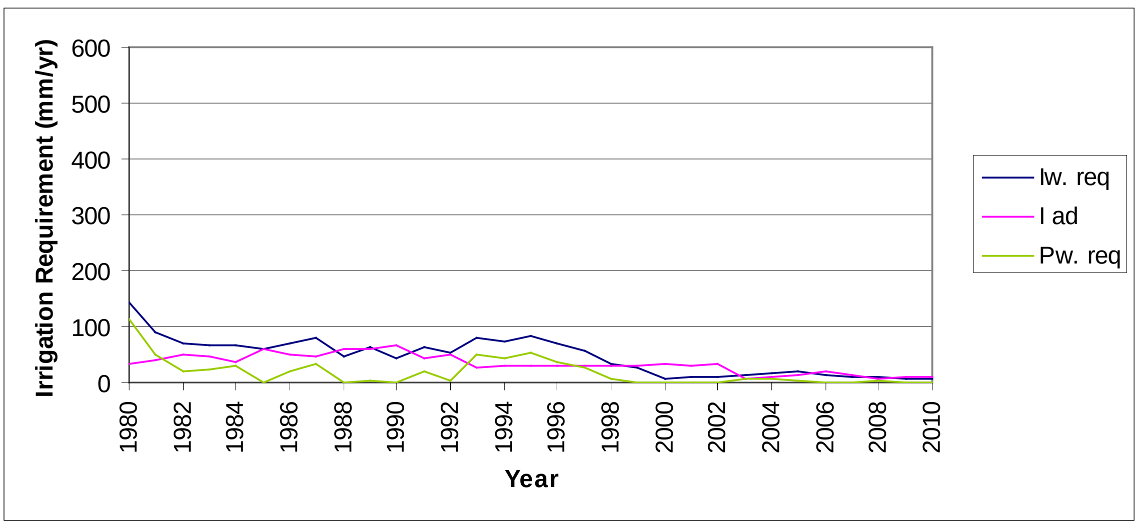

Figure A.12. Irrigation water requirement (Iw. req), imports (I ad) and extractions (Pw. req) for Patillas modeling area

Figure A.13. Net irrigation water demand (I) and effective precipitation (Eff. P) for Salinas modeling area

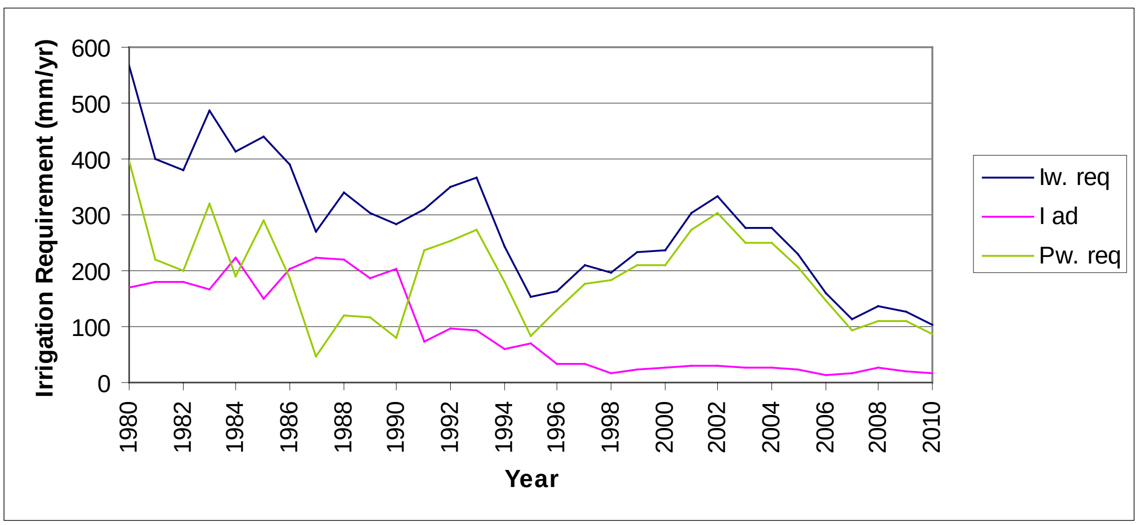

Figure A.14. Irrigation water requirement (Iw. req), imports (I ad) and extractions (Pw. req) for Salinas modeling area