Application of GIS and AHP Analysis for the Delineation of Potential Groundwater Bearing Zones in Fractured Rock Aquifers

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Abstract *— Groundwater extraction accounts for around 29% of Puerto Rico's water demand. About 50% of the withdrawn water from aquifers serves the needs of "Non PRASA" communities mainly located in the central province of the island. In this scenario, it is essentially needed an effective approach to asses and explore abundant and sustainable groundwater resources, to better serve future water demand. This study presents an approach to locate, delineate and estimate the recharge of groundwater bearing zones using the Geographical Information System (GIS). The methodology was used to pinpoint groundwater potential zones in fractured rock aquifers located in Rio de La Plata Watershed. To achieve the study objective, various thematic layers of hydrology, hydrogeology and geomorphology parameters were processed into raster features in ArcGIS 10.5 software. A weight overlay of these parameters was then analyzed by means of an Analytic Hierarchy Process (AHP), generating a groundwater potential map. Groundwater bearings zones identify by the model demonstrate agreement with USGS and PRASA well inventory. Results validate the relevance of GIS and AHP as effective tools for assessment, management and future groundwater exploration in the island.*

Key Terms *— Analytic Hierarchy Process, Hydrogeology, Geographic Information System, Groundwater Potential Zones.*

INTRODUCTION

Groundwater is a valuable natural resource that represents 30% of the fresh water available in the planet [1], making it much more abundant than surface water. Clean and plentiful groundwater is key to sustain life on earth, especially nowadays when water scarcity is becoming an important issue in many countries around the world. The inadequate supply of water is mainly due to an increase in consumption and shortage of surface water. Drastically changing climate patterns, high population density, uneven distribution of water resources and its demand spatially and temporally, economic development, are among the many factors impacting surface water supplies [2]. The lack of a sustainable water resource not only affects communities but also industrial and agricultural activities, which represent the backbone of the economic development. Recent studies indicate that groundwater is becoming the main source of water supply for many countries [3], and Puerto Rico is not an exception. Therefore, recognizing the importance of these natural resources and optimal usage of them, contributes to a sustainable and permanent usage of this natural wealth.

As opposed to surface water, the access to groundwater takes more work and cost more, especially in remote areas where the resource is much needed. Currently, the use of geographical information system (GIS) is being applied to the detection of areas with potential of groundwater occurrence and has proven to be a cost effective and less time consuming alternative compared to ordinary methods. The use of GIS is fundamental for effectively addressing groundwater exploration and spatial data understanding of the hydrogeological aspects governing the subsurface movement of water through a certain region of study. Some of the spatial data study parameters for groundwater potential zone mapping includes, but are not limited to aspects such as geology, lineament density, geomorphology, slope, rainfall, drainage density, soil type and land cover.

One crucial step to create an effective potential groundwater map resides in the proper selection of

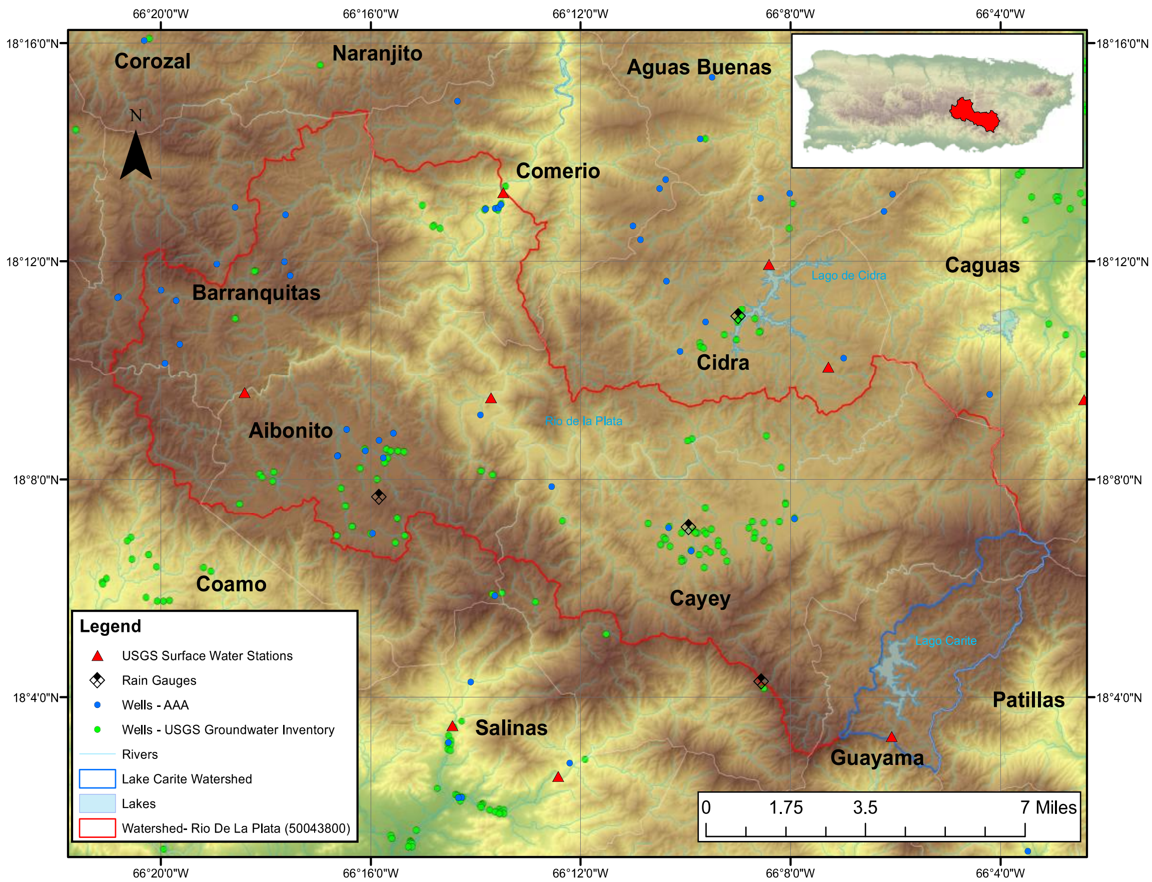

Figure 1
Location Map of the Study Area

a methodology to elaborate the groundwater potential index. There are a variety of methods applied for this purpose [4], some of them are: frequency ratio, weights of evidence and AHP. In this particularly case, the chosen method for the present study was the Analytic Hierarchy Process (AHP). This technique relies on the construction of decision matrixes to define the weight of importance of the different geological, hydrological and hydrogeological parameters. Once the matrix is normalized and resolved, weights are assigned to the different raster layers of the thematic maps and an overlay weight analysis is performed in ArcGIS environment. The final outcome of the process is a potential groundwater map with intervals ranging from very good to poor conditions. Results obtained with the methodology forecasted very good and good conditions for groundwater occurrence, in the locations of PRASA and USGS wells inventory.

STUDY AREA

The study area is located in the Rio de la Plata Watershed (Figure 1) as defined by the USGS surface water station 50043800, covering the municipalities of Comerio, Cayey, Barranquitas, Coamo and Guayama. The drainage area of the catchment is of about 109.6 square miles, excluding an area of 8.2 square miles upstream from Lago Carite, the flow of which is diverted to Río Guamaní. The Rio de La Plata watershed lies between latitudes 18° 14’45” N and 18° 02’37” N, longitudes 66° 20’58” W and 66° 03’05” W. The area is part of the interior province of the island, which constitutes 59% of the total area of Puerto Rico, covering 1,992 square miles of steep mountainous terrain [5]. The annual normal rainfall varies from 57.39 to 75.15 inches. The area has a land cover mainly composed of herbaceous and forested terrain, with clustered concentration of urban development at the center of the municipalities. In many areas of the municipalities of Aibonito, San Lorenzo, Coamo, and Comerio, scattered wells fed by water flow through fractures in the volcanic rocks. Studies of minimum flows in fractured rock aquifers have determined recharge ratios similar to the recharge of aquifers of productive limestone in the northern region of Puerto Rico. It is estimated a net recharge of 20 inches per year at Comerio [6].

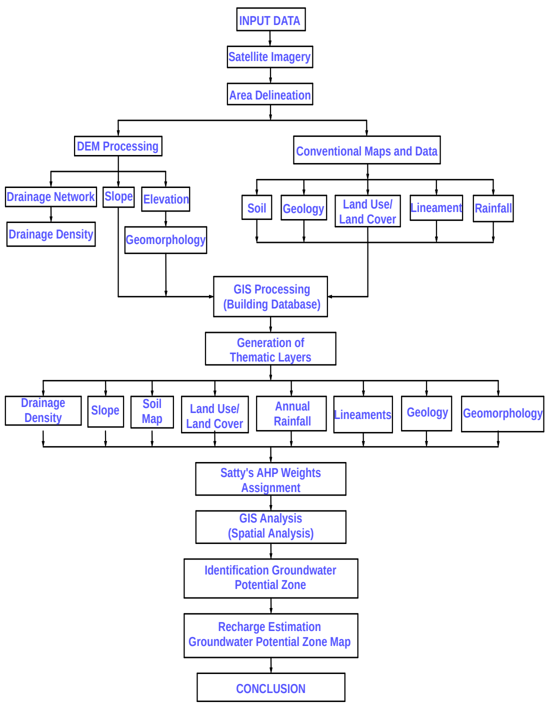

Figure 2
Flow Chart for Delineation of Groundwater Potential Zone

METHODOLOGY

The methodology workflow for the delineation of groundwater potential zone is presented in Figure 2. The 1/3 arc-second digital elevation model (DEM) was obtained from the USGS National Map. As part of the DEM pre-processing, it was necessary to merge the raster tiles to construct the topographical map for the study area. Flow accumulation and stream flow maps where developed prior to the delineation of the stream network. The slope raster layer was prepared from the USGS 1/3 arc-second DEM in the ArcGIS spatial analyst. Rainfall map was processed using the normal annual precipitation values provided by NOAA. The gauge station data was spatially interpolated using the Inverse Distance Weighted (IDW), to obtain the distributed precipitation map. The drainage density and lineament density raster maps were processed through the implementation of line density analysis in ArcGIS. Geomorphology of the study area was mapped by means of Hammond's method.

The soil, land cover/land use and geology thematic layer where downloaded from the USDA and USGS online spatial database. These thematic layers where converted into raster format and reclassified, as per AHP weights assigned. Subsequently, a potential groundwater bearing zone map was constructed by the weighted overlay analysis (WOA) method using the spatial analysis tool in ArcGIS 10.5. The WOA basically assigns weight to each individual parameter of each thematic map, according to the analytic hierarchy process (AHP).

ANALYTIC HIERARCHY PROCESS (AHP)

Developed by Thomas L. Satty (1980), the analytic hierarchy process (AHP) is a structured mathematical method used to organize and analyze complex decision-making [7]. It is based on the construction of a pairwise comparison matrix, which is assembled for each thematic map using a scale of importance of nine points. Once the matrix is resolved, each weight is assigned to the values or ranges of each thematic map, thus establishing a hierarchy order for those parameters that define the occurrence of groundwater. Later on, all the thematic maps where subjected to a weighted overlay analysis run though the Spatial Analysis Tool in ArcGIS 10.5, in order to obtain groundwater potential zone map.

	G	GM	LD	S	ST	DD	LU/LC	R	Weight
Geology	1	2	2	4	5	6	7	8	*31%*
Geomorphology	1/2	1	2	3	4	5	6	7	*23%*
Lineament Density	1/2	1/2	1	2	3	4	6	6	*17%*
Slope	1/4	1/3	1/2	1	2	3	5	4	*11%*
Soil Type	1/5	1/4	1/3	1/2	1	2	4	5	*8%*
Drainage Density	1/6	1/5	1/4	1/3	1/2	1	2	3	*5%*
Land Use and Land Cover	1/7	1/6	1/6	1/5	1/4	1/2	1	2	*3%*
Rainfall	1/8	1/7	1/6	1/4	1/5	1/3	1/2	1	*2%*
Consistency Ratio = 0.05									

Figure 3
AHP Weight for All Factors Map

Results and Discussion

The following information explains the outcome of this research.

Integrated GIS Modeling and Weighted Analysis

In order to achieve the objectives of the present study, a GIS model was constructed integrating various raster layers in the ArcGIS 10.5 environment. The thematic map layers used for the delimitation of the potential zone mapping included spatial distributed parameters such as: drainage density, rainfall, slope, soil, land use/land cover, lineament density, geology and geomorphology. Each layer was converted to raster format and reclassified according to the weights assigned in the AHP analysis. Subsequently, AHP method was applied to the parameter of groundwater potential and a WOA procedure was conducted multiplying each individual class by the maps scores and then adding the results. Essentially, ArcGIS 10.5 software assigned to each raster a percentage of influence and multiplied it by their AHP cell value. Then, the results where added together to create the output raster and the values where arranged into five classes: very good, good, moderate, fair and poor.

The relative weights assigned to each map layer were calculated in a preprogrammed Excel spreadsheet solver, for the Satty AHP matrixes. The methodology involved a construction of a wise comparison matrix (Figure 3) in pairs to compare each class and then a standardized matrix was assembled. A consistency ratio (CR) was calculated with each matrix. Values for CR equal to 0.10 or less were considered acceptable, as stated in the method. In the case of CR values higher than 0.10, they were re-evaluated until reaching the ideal consistency, according to Satty method.

Drainage Density

The drainage density is defined as the linear units of stream channels per drainage area. Drainage density is an inverse function of permeability [8]. In terms of infiltration, runoff percolation is controlled by the permeability of the rock. Essentially, the presence of fractured rock in the soil overlain produces less surface runoff, while impermeable rock increases it. The allocation of high drainage density zones within a study area represents a less likely potential of groundwater occurrence. A dense network of stream channels drains water more quickly to a river, therefore limiting the exposure of the soil to infiltration and moisture. The drainage density for the study area was calculated with the spatial analyst tool in ArcGIS 10.5 software and divided into four classes. High drainage density was recorded along the Rio de La Plata main stream path (Figure 4), with a value of 2.7 km/km². Such value of drainage density may be due to steep slopes, limited vegetation cover and large frequency of tributaries. Most of the study area registered values of less than 2.0 km/km², what suggests the existence of permeable rock, more vegetative cover, lower channel frequency and a higher potential of groundwater occurrence within those zones.

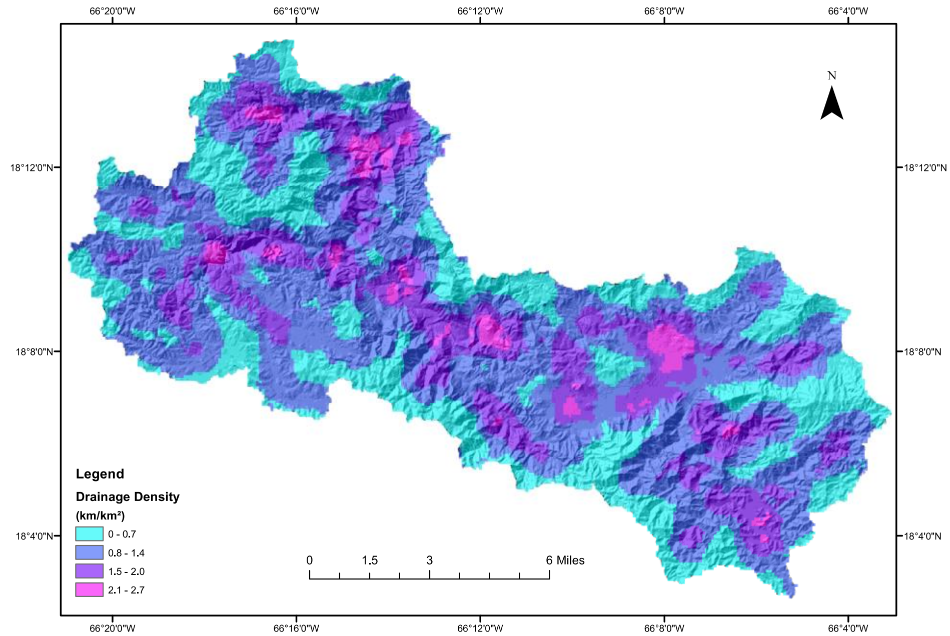

Figure 4
Drainage Density Map of the Study Area

Rainfall

Precipitation is one of the main indicators of groundwater potential. This hydrological variable is directly affected by several factors, among which are the geology, topography and vegetation. In particular, the study area geological layer is mostly made up of igneous and sedimentary rock with some degree of fracture. In this case, the existence of herbaceous and forest cover can greatly contribute to the weathering or enlargement of rock fractures, thus promoting the infiltration of rainfall into the aquifers. The annual precipitation (Figure 5) for the study area ranges from 57.39 inches to 76.15 inches. Annual values of precipitation normals are typically the average values during the 30-year period. Unlike the averages, daily normal are computed using a harmonic fit, a statistical method that dampens the effects of outliers, creating a smooth transition within time intervals [9]. Precipitation average normals where recorded for all gauge stations available in Puerto Rico. The rainfall data was downloaded through the Climate Data Online (CDO), an electronic library of the National Oceanic and Atmospheric Administration NOAA. Rainfall distribution though the area of study was delineated with the inverse distance weighted (IDW) interpolation tool, available in the spatial analyst toolbox in ArcGIS 10.5.

Slope

Slope is an important factor to consider in the groundwater potential zone delimitation. In general, terrain with steep slopes accelerates the flow of runoff, thus minimizing the rate of possible infiltration of water into the soil subsurface. Hence, terrain with less degree of slope translates into a higher potential of groundwater occurrence within the area of study. The slope map of the study area was constructed based on the 1/3 arc-second digital elevation model (DEM). Basically, the ArcGIS 10.5 spatial analyst slope tool calculates the rate of change in value from each cell to its neighbors, using a 3 x 3 cell neighborhood around the center cell. The slope map for the basin area was divided into five classes: 0°- 8° (flat), 9°- 15° (gentle), 17°- 23° (moderate), 24°- 32° (steep) and 33°-74° (very steep). Slope analysis of the

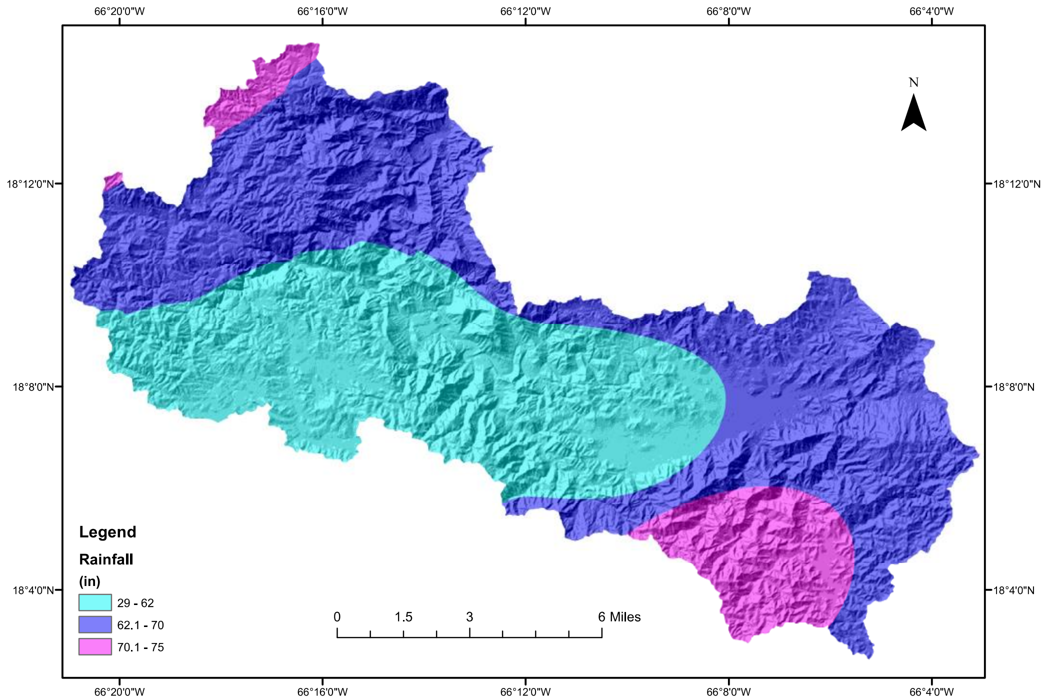

Figure 5
Rainfall Map of the Study Area

study area showed steep and moderate terrain topography prevails in the region (Figure 6), whereas very steep slopes concentrated in the northwest portion of the watershed.

Soil

In terms of soil, the map layer was classified into hydrological soil groups, as per Soil Survey Geographic Database (SSURGO), distributed by the National Soil Conservation Service (NRCS), an office of the United States Department of Agriculture (USDA). Hydrological soil groups are based on soil's runoff potential and classified as A, B, C and D. Soils with an A classification have less runoff potential and higher infiltration rates, thus providing great amount of water percolation to the subsoil environment. In turns, soil group D type of soils tends to be the opposite, contributing to runoff and the less likely to aquifer recharge. As per GIS analysis performed, moderate to slow infiltration rates prevail in great part of the Rio de la Plata watershed.

Land Use/Land Cover

Major part of the Rio de la Plata watershed is covered by evergreen forest and herbaceous ground cover. Around 86% of the total area is composed of vegetative cover. The data layer used for the Land Use raster processing was the National Land Cover Database Commonwealth of Puerto Rico Land Cover Layer (NLCD), as produced by the International Institute of Tropical Forestry (IITF). NLCD data layers were developed through a cooperative project conducted by the Multi Resolution Land Characteristics (MRLC) Consortium. The MRLC Consortium is a partnership of federal agencies, consisting of the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Environmental Protection Agency (EPA), the U.S. Department of Agriculture (USDA), the U.S. Forest Service (USFS), the National Park Service (NPS), the U.S. Fish and Wildlife Service (FWS), the Bureau of Land Management (BLM)

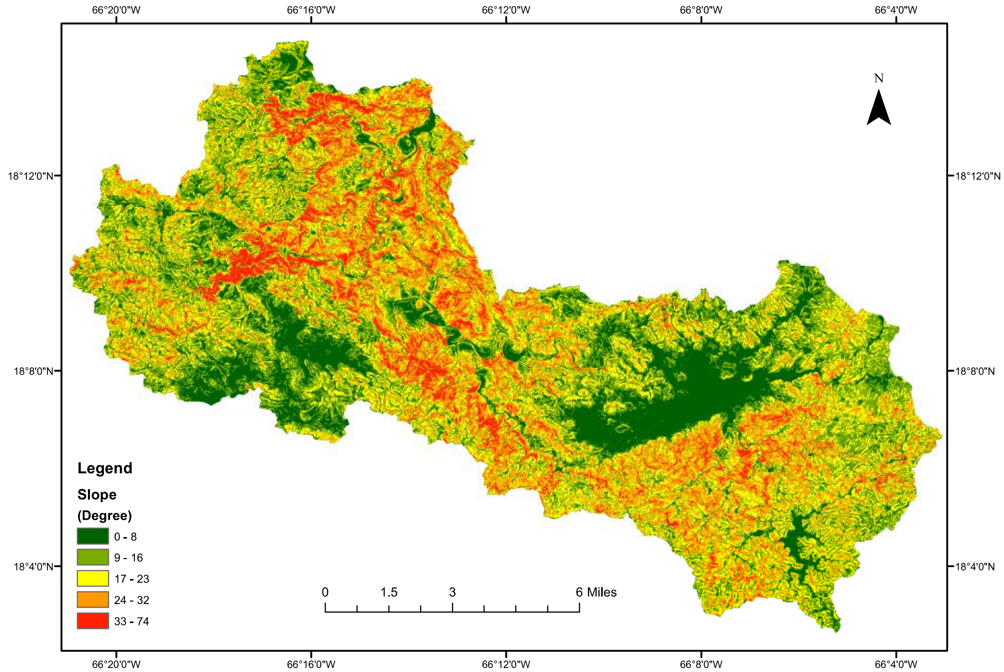

Figure 6
Slope Map of the Study Area

and the USDA Natural Resources Conservation Service (NRCS) [10].

Lineament Density

Lineament density map was processed using the online spatial data layer titled Geology, geochemistry, geophysics, mineral occurrences, and mineral resource assessment for the commonwealth of Puerto Rico [11], as distributed for web access by the USGS. The lineament density refers to the faulting and fracture length observed in a particular area of interest. Just like the drainage density it is expressed in linear units per area, and the analysis is conducted with the line density tool available in the ArcGIS 10.5 spatial analyst toolbox. Lineament represents the zones of rock fracture resulting in secondary porosity and permeability [12]. Groundwater availability in the central province of Puerto Rico is limited mainly to fractured rock aquifers highly dependent on secondary permeability. In this particular case, geomorphology of the region and geological features such as lineaments and rock faulting play a key role in the identification of groundwater prone zones. Although the geological conditions in the center region of the island make the extraction of a large volume of groundwater complicated, the reality is that these aquifers of local faults and fractured rock have a significant potential if these geological conditions are located. High lineament density concentrates in the center and northwest portion of the study area (Figure 7), with a maximum of 3.67 km/km^2, located in the municipalities of Comerio, Barranquitas and Aibonito.

Geology

The geology of the central province of Puerto Rico is characterized by the predominance of volcanic rocks, little studied and complex due to its high degree of fractures. These rocks of volcanic origin date from the Mesozoic era, about 250 million years ago. A variety of studies of Puerto Rico's geology have been published by the Academy of Sciences of New York between 1915 and 1933, Meyerhoff (1931, 1933), Zapp et al.

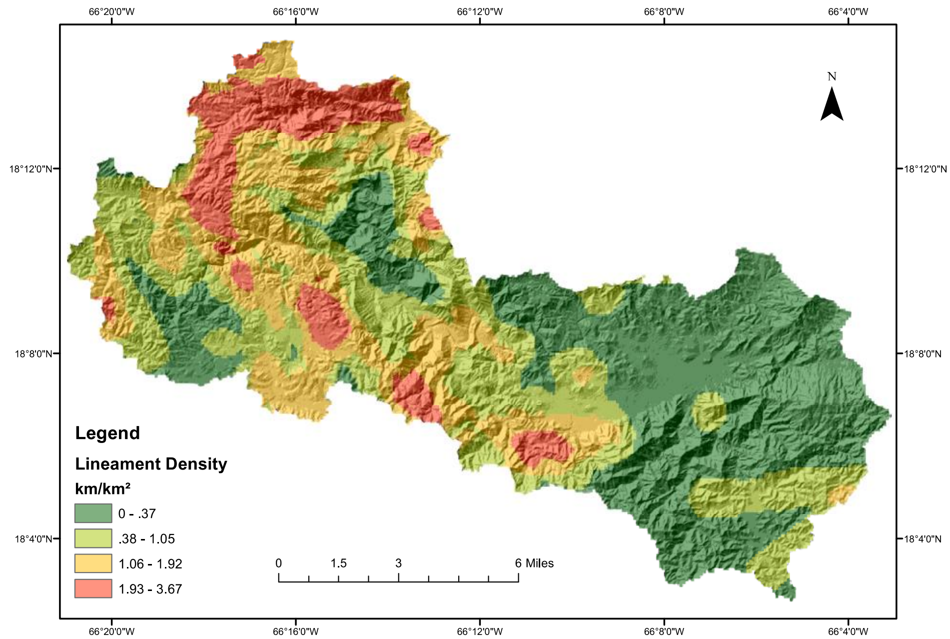

Figure 7
Lineament Density Map of the Study Area

(1948), Briggs and Ackers (1965), Monroe (1980), Seigle and Moussa (1984) and more recently by Renken et al. (2002). In general, the geology of Puerto Rico is varied for its relatively small surface area, and it is an important factor that influences the availability and quality of water resources [13]. The study area is mainly underlain by igneous and sedimentary rock with some alluvium concentrated along the river valleys. GIS analysis indicate, about 92% of the total area is underlay with igneous and sedimentary rock.

Geomorphology

The geomorphology of the study area was mapped using the Hammond's method, as reworked by Morgan et al (2005). Morgan's workflow involves a set of operations that includes DEM raster manipulation, development of focal statics and reclassification routines to define the landform characteristics of the watershed under study. In essence, the landform of the study area is a function of the sum of the slope, relief and profile of the region [14]. The geomorphology of the watershed is predominantly mountains and hills, but some valleys are abundant in the municipalities of Cayey and Aibonito.

Delineation of Groundwater Potential Zone Map

The Groundwater Potential Zones Map (Figure 8) was achieved by the integration of the thematic layers, as previously discussed. Delineation process was made by the interpretation of the spatial distributed hydrogeological characteristics of the Rio de la Plata watershed. As part of the study there were identify eight indicators of groundwater occurrence based on the existence of fractured rock aquifers within the region. Thus, relative importance was granted to lineament density, geology and geomorphology of the watershed. Groundwater Potential Zones Map (Figure 8) was divided into five classes namely very good, good, moderate, fair and poor. The results demonstrate that very good and good conditions for groundwater potential are concentrated in the valleys of Cayey, central part of Aibonito and at the north of the watershed, where the municipalities of Barranquitas and Comerío are located. This is mainly due to the distribution

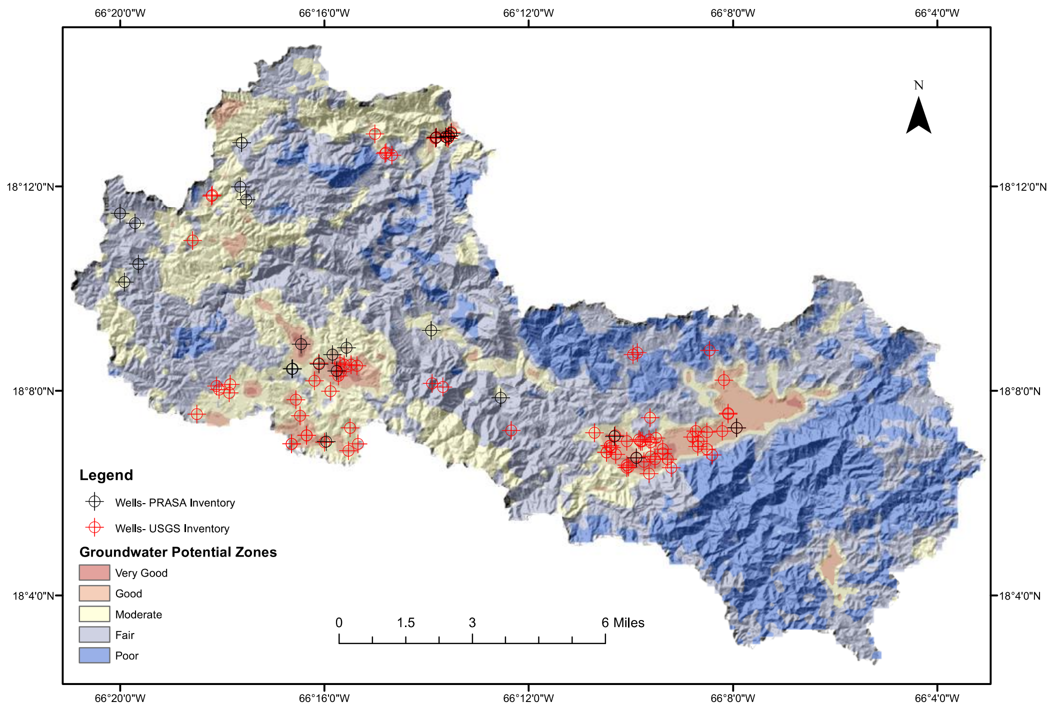

Figure 8
Groundwater Potential Zones Map

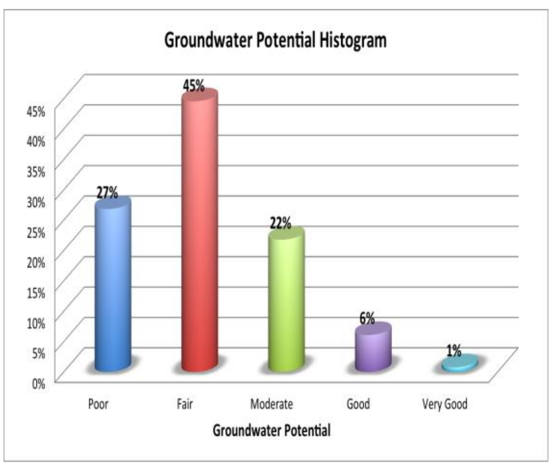

Figure 9
Groundwater Potential Histogram

of alluvial plains in the municipality of Cayey and the fact that there is high lineament density concentration up in the north of the Rio de la Plata basin, in the municipalities of Aibonito, Barranquitas and Comerío. As illustrated in the Groundwater Potential Histogram (Figure 9), about 27% of the total area falls under the poor zone, 45% under fair zone, 22% under moderate zone, 6% under 'good' zone and 1% under very good groundwater potential zone.

Groundwater Recharge Estimate

The recharge estimate was obtained by means of a simplified calculation with proposed recharge rates adapted from UN 1967 [15]. The recharge ratios for the study area where assigned in accordance to the groundwater potential zone classes: 0.45 (Very Good), 0.35 (Good), 0.20 (Moderate), 0.07 (Fair) and 0.03 (Poor). The estimated recharge for the study area was calculated as 7.08 in/year, with an infiltration rate of about 11% of precipitation per year.

Conclusions

The application of GIS and AHP proved to be an effective and powerful tool for assessing the groundwater potential of fractured rock aquifers in the central region of Puerto Rico. As demonstrated, the occurrence of groundwater in the region is mainly controlled by rock fracture, geological lineament and geomorphology and to a less extent slope, drainage and rainfall. The groundwater potential zone map of the study area shows total agreement with the location of the USGS and PRASA groundwater extraction wells inventory at

Rio de la Plata basin. Groundwater recharge was estimated in 7.08 in/year, which translates to an infiltration of 11% of the annual precipitation in the watershed. The recharge calculated with the GIS and AHP method coincides to a large extent with the net recharge estimates of the Department of Natural and Environmental Resources of Puerto Rico (DRNA). According to this agency estimates, the aquifers of the interior of Puerto Rico average a recharge of between 10 to 15% of the annual rainfall.

GIS and AHP analysis can be applied extensively for the exploration of groundwater in areas with rugged topography, where access is limited. This method is applicable to all types of aquifers and it could be a useful tool for the identification and protection of recharge areas across the island. In addition, this method would be an excellent instrument to plan the location of future artificial groundwater recharge projects.

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