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Analysis of Groundwater in Puerto Rico

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Abstract During rainfall events, the aquifers in Puerto Rico capture a small fraction of the rainfall and sometimes can store it for years. Organic pollutants are degraded over time by microbial and chemical processes. The shorter the travel time between raindrop and aquifer recharge the greater is the risk of contamination. Existing data from non-pumping observation wells have been used to identify three areas at risk from superficial contamination. High-risk areas have a high correlation between depth-to-water and temperature or respond quickly to rainfall events. The high-risk areas are in Florida and in the adjoining municipality of Quebradrillas/Camuy and Manatí/Vega Baja. It is proposed that production wells in the high-risk areas be instrumented to measure the rainfall and the temperature and specific conductance of the pumped water and the rainwater. The hypothesis of this proposed experiment is that in the high-risk areas the water pumped from the production well will show a reduction of temperature and specific conductance within 24 hours of a heavy rainfall event. In this manner the travel time from rain drop to aquifer recharge can be measured. The proposed paper will provide concrete data to improve the management of groundwater resources in Puerto Rico.

Keywords: *Groundwater, Acquifers, Puerto Rico, rainfall*

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1. Introduction

Puerto Rico is an oceanic tropical island located between the Caribbean Sea and the Atlantic Ocean. The estimated population in 2014 was 3.5 million people [40]. Groundwater provides 16 percent of the water used in Puerto Rico [21]. Groundwater becomes more important when surface water is unavailable due to drought, as happened in 2015. At the height of the drought many homes in the San Juan metropolitan area had water two days per week [14]. Puerto Rico has one desalinization plant that produces 7600 cubic meters of water per day [26], which represents about 0.3 percent of total water usage. Desalination is energy intensive, and on an island where 98 percent of the electricity is produced by burning fossil fuels [26], increased use of desalination will increase air pollution and emissions of climate changing gasses. The goals of this study are to demonstrate a new use for existing groundwater temperature data and to enhance the science that is used to manage groundwater resources in Puerto Rico. It is also expected that the techniques developed here will be useful in other parts of the world.

“Intrinsic vulnerability represents the inherent hydrogeological and geological characteristics which determine the sensitivity of groundwater to contamination by human activities; the term refers essentially to risk associated to non-point sources. Intrinsic vulnerability considers all kind of contaminants, opposed to specific vulnerability” [8].

In both the United States and Europe a variety of schemes have been developed to rank aquifer vulnerability. These schemes are usually based on the geographical distribution of characteristics like depth-to-water, aquifer media, and recharge. There is no consensus about which scheme works better [10]. This study will use the correlation between groundwater levels and water temperature and response time to rain events to examine the intrinsic vulnerability of aquifers in Puerto Rico.

Heat can be used as a tracer [1], in many environments, rainfall is colder than ambient conditions. In Kentucky, USA, a spring was instrumented; after a rain event, the discharge rose rapidly but the water temperature declined only after a lag. The water that discharged between the rise in discharge and the fall in temperature was interpreted as the storage in the aquifer that drains into the spring [34].

In the Alps, wells are often drilled next to rivers, and government regulations in Switzerland and Germany require a travel time between the river and the production well of 10 and 50 days respectively. The transmission of the diurnal water temperature cycle of the river into the aquifer was used to measure the travel time from river to monitoring equipment located within one to two meters of the river [12]. At mid-latitudes, which have a large annual air temperature cycle the seasonal cycle can be detected up to 50 m away from the river [20]. These techniques will probably not be useful in Puerto Rico where both the diurnal and annual temperature cycles are smaller than in temperate, continental regions.

Organic contaminants are broken down into harmless components by microbial and chemical processes that take time. The travel time between raindrop and aquifer recharge is inversely proportional to the threat to groundwater resources. Pesticides are broken down faster in soils than in aquifers because the soil has more dissolved oxygen, minerals, organic material, surface area, and microbes than aquifers. The herbicide alachlor has a degradation half-life of around 4 years in aquifers but only 20 days in soil [35]. The median degradation half-life in soil of 11 pesticides detected in groundwater in Santa Isabel, Puerto Rico is 60 days [32]. Atrazine is a pesticide that degrades to deethylatrazine at a predictable rate and the ratio of these two chemicals was used to identify a region in western Santa Isabel where the groundwater is older than average [32].

Compared to old aquifer water, recharge water is cold, lower in dissolved solids, and higher in suspended solids, oxygen, nutrients, and microbes. Of these variables, temperature and specific conductance are the easiest to measure in the field with electronic sensors that can collect data at high frequency. If the rainwater reaches a production well quickly then it will still be cold and the pumped water will be cooler by the fraction of the pumped water that is recently arrived recharge water. The specific conductance will probably take longer than temperature to reach equilibrium. There are large quantities of existing hourly groundwater temperature data collected at non-pumping observation wells. There are no existing high frequency data for any of the other variables on the list. In Puerto Rico, groundwater is an important backup when surface water is unavailable due to drought.

The two major aquifers on the island are the karst North Coast Limestone (NCL) aquifer and the alluvial South Coastal Plain (SCP) aquifer [19,27] describes the geology, biology, and land use of the karst of Puerto Rico and calls for it to be set aside for conservation. The NCL is a northward sloping sedimentary wedge that was laid down during the Oligocene and Miocene. The five geologic units of the NCL, from oldest to newest, are the San Sebastian Formation, the Lares Limestone, the Cibao Formation, the Aguada Limestone, and the Aymamón Limestone. The dip is northward and averages five degrees. The list above is also the order that the formations outcrop from south to north. In places, particularly in the east, the NCL is overlain by unconsolidated Quatenary deposits. A map of Puerto Rico and a geologic map of the North Coast Limestone are shown in Figure 1.

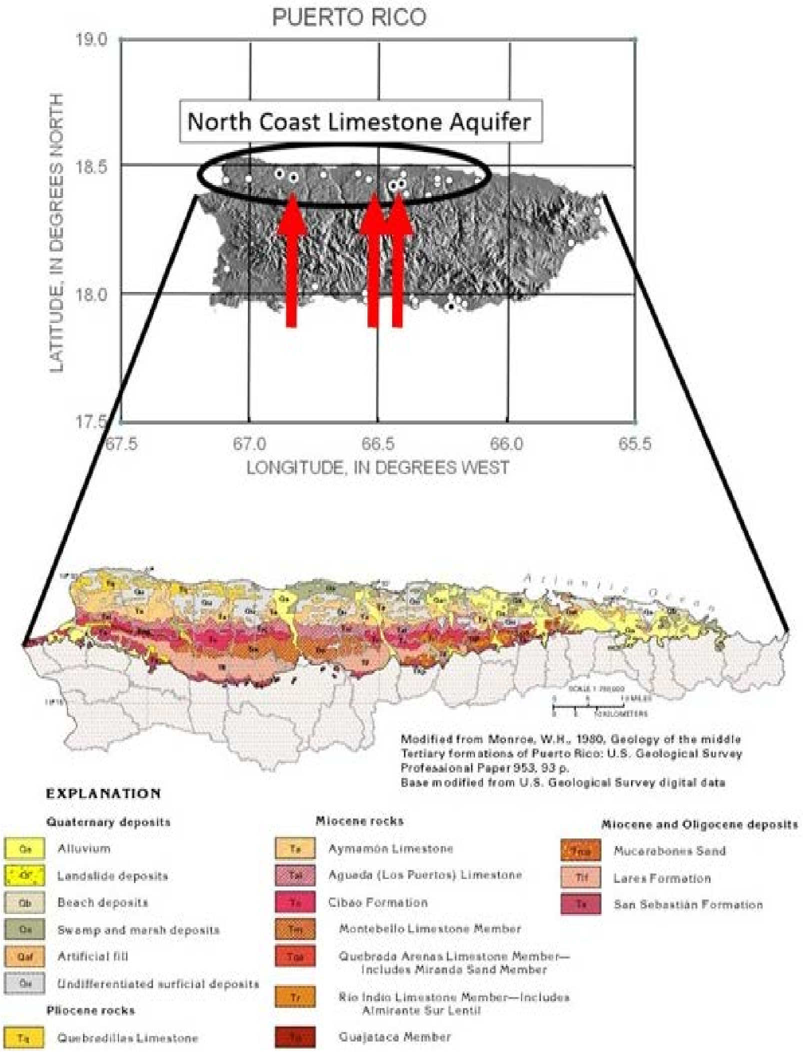

Figure 1. Location of the observation wells used in the study (upper panel) and a geologic map of the North Coast Limestone aquifer (NCL). The circles with black centers are the five observation wells with a Pearson correlation coefficient between depth-to-water and water temperature above 0.85. The highly correlated station in Salinas, in the South Coastal Plain aquifer, was excluded from the study because the water level is controlled by tides and the pumping schedule of nearby production wells and not rainfall. The three red arrows show the locations of the high-risk areas in the NCL aquifer. The base map for the upper panel is from the United States Geological Survey and the lower panel is from [22]

Hydrogeologically, the NCL is divided into two limestone dominated productive units with high hydraulic conductivity. The productive units are separated and underlain by clay-rich units of low hydraulic conductivity [27]. The upper part of the Cibao Formation is high in clay and low in hydraulic conductivity. This part of the Cibao supports surface streams while the rest of the NCL is dominated by subsurface flow. The upper unit of the NCL includes the Aguada and Aymamón Limestones. The lower unit of the NCL includes the Lares Limestone and in some areas permeable parts of the Cibao formation such as the Montebello Limestone. The lower unit has a longer travel time between rainfall and aquifer recharge and the methods of this study would probably be less useful. In this study, there is more data from the upper unit than from the lower unit.

In Puerto Rico, there is a longstanding discussion about how to digitally model the NCL aquifer with its mix of low-hydraulic conductivity matrix interspersed with fractures and conduits of higher hydraulic conductivity. Digital groundwater models have been developed for the NCL aquifer in the area of Barceloneta [36], in the north central coast between the Río Camuy and Río Grande de Manatí [37], and in the Manati-Vega Baja area [3] and all of these models have estimated an equivalent hydraulic conductivity. In the opinion of [9], there are not enough data to do a good job of modeling the NCL.

The SCP aquifer is the most important aquifer in southern Puerto Rico, which is drier than the north of the island [4]. The SCP aquifer is 70 km long and 3 to 8 km wide. It consists of a series of fan deposits that have coalesced. The size of the particles ranges from boulder to silt. The depositional environment is complex and has included downward moving grabens [27]. The SCP aquifer is recharged both by direct rainfall and from intermittent streams that flow out of the mountains that are north of the coastal plain. Often these streams are kilometers long and permanent in the mountains and then the water sinks when the stream crosses onto the alluvium. Some of the streams may not flow into the ocean for months during the dry season.

2. Data Availability

This study will describe how existing data from non-pumping observation wells operated by the United States Geological Survey (USGS) can be used to identify areas with shorter travel times from raindrop to aquifer recharge and are at higher risk from superficial contamination. For most of the twentieth century water levels in observation wells were measured by some type of float-counterweight system. Early in the twenty first century the USGS Caribbean Florida Water Science Center (USGS-CFWSC) in Puerto Rico changed from floats to pressure transducers. Floats detect the density difference at the air-water interface while pressure transducers are located at a fixed location below the lowest water level ever recorded. In a pressure transducer the pressure and temperature are measured and then the water level is calculated. The hourly water temperature data were collected with no intention of using the data except to calculate the water level.

If the rainwater reaches and recharges the aquifer within a few hours, while it is still cold, then there will be a correlation between depth-to-water and water temperature, both will decline after a heavy rain event. If the rainwater takes months to travel from the surface to the aquifer then it will have warmed to ambient temperature and there will be no correlation between depth-to-water and water temperature. A second method to identify areas in the aquifer with a shorter response time is to instrument the well with a rain gage. After a rainfall event, the time until the water level rises can be measured. A water level in an observation well that rises quickly after a rainfall event does not prove that the water entering the well is new recharge water from the recharge event. A second possibility is that the rainfall event created a pressure wave which moved ahead of the new recharge water and forced old aquifer water into the well.

The journey of a rain drop that will recharge an aquifer has three components: First as runoff the water quickly moves across the land surface until an increase in the hydraulic conductivity allows it to drop underground. The second leg is downward until it reaches the water table. In the third and longest section, it recharges the aquifer and the water slowly moves horizontally to its discharge point in a spring, seep, or pumping well. The speed of the water is slower with each of the three legs of the journey.

When the rain drop hits the land surface it is relatively cold, saturated with oxygen, and low in dissolved and suspended solids. There has been little use of tracers in Puerto Rico [9]. In Puerto Rico there are a small number of studies that document the water quality of rain [23], and more that document the water quality of runoff [5,24,29,30,31]. As it crosses the land surface the runoff picks up sediments, organic material, and microbes. Runoff water in Puerto Rico often has the color of coffee with milk.

The second leg of the journey is transient, occurs underground, and is almost undocumented. In the NCL the closed depressions where the runoff goes underground are often clogged with mats of decomposing leaves and logs mixed with inorganic sediments. The only study that looks at the connection between the surface and the aquifer is [33] which classified 58 springs as conduit and nine as diffuse. Conduit springs are well connected to the surface and during rainfall events conduit springs undergo a rapid change in discharge and water quality including sediment load. Diffuse springs integrate water over a long period and do not undergo dramatic changes during rainfall events. Heat can be used as a tracer to study the water as moves vertically towards the water table.

Unlike the transient conditions in the flow of runoff and the vertical stage of recharge water movement, the third leg of the journey, the horizontal flowing groundwater below the water table is a permanent feature and is easier to study. In Puerto Rico thousands of wells have been drilled and the vast majority is not pumped. According to the [41], the National Water Information System (NWIS) has on the webpage (Internet) 2492 wells with at least one water level and 79 with 100 or more. At 87 wells water level data have been collected in the past year.

Compared to some parts of the world, Puerto Rico has vast amounts of groundwater data and much of it is available on the Internet. At the same time there are limitations to the groundwater data that exists for Puerto Rico. NWIS has 1487 wells in Puerto Rico or the U.S. Virgin Islands with at least one water quality sample but the first sampling of groundwater quality at regular intervals began in 2011 [41]. Some published groundwater models have been based on limited amounts of data. Data are sparse for the model of northwest Puerto Rico from Aguadilla to the Río Camuy [39]. The calibration of the groundwater model in Santa Isabel is almost entirely based on data from the Alomar 1 observation well [16]. Groundwater models have used hydraulic conductivity data generated from slug tests or specific capacity data that only measure the aquifer properties within a few meters of the test well [9]. Multi-well aquifer tests which could provide data over hundreds of meter are more expensive but have seldom been performed. [17] Is a study using a groundwater model in the SCP in Salinas and noted the lack of multi-well aquifer tests.

Karst aquifers are dominated by solution processes. Dissolution occurs more rapidly in environments that are warm, wet, and have high levels of carbon dioxide. Puerto Rico is tropical and is warmer than non-tropical areas. The average annual rainfall in Puerto Rico is 1654 mm [18] and this is more than in most places in the world. In the humid tropics the biomass density is higher than in non-tropical areas and the decomposition of this biomass raises the concentration of carbon dioxide in the soil. In the tropics, secondary porosity will develop in limestone more rapidly than in non-tropical areas.

There are no studies on the travel time from the surface to the aquifer. The upper unit of the NCL is recharged almost exclusively by direct rainfall. The lower unit of the NCL is recharged by direct rainfall and also by streams that form on the volcanic rocks to the south and then disappear underground when they cross onto the karst rocks. In the karst NCL, aquifer recharge occurs when the monthly rainfall exceeds 200 mm [15]. In all the studied aquifers the generalized direction of flow is towards the ocean. The volcanic core of the island has fractured-rock aquifers that contribute to maintaining base flows in the rivers but there is little groundwater production or data. It is commonly assumed that the karst NCL aquifer is at greater risk from the rapid movement of superficial contaminants than the alluvial SCP aquifer. However the intrinsic vulnerability of the NCL aquifer has not been tested. A key question is if the NCL aquifer has consistent vulnerability or needs to be broken down into smaller units.

Much of what we know about groundwater in Puerto Rico is from the observation wells maintained by the USGS-CFWSC and the data in this study is from a subset of these wells. Typically in a groundwater study, the USGS-CFWSC drills some piezometers, after the short-term project, some of these piezometers become part of the long-term network. The USGS-CFWSC constructed piezometers used in this study in Naguabo [11,17,24,38]. These stations have been used to study the water-level fluctuations in observation wells [28]. Long-term water level data from these observation wells has been used to calibrate groundwater models in Santa Isabel [16,17]. A second source of observation well is wells that were drilled to be production wells but then abandoned.

Two of the observation wells used in this study Hill 2, Manatí and Palo Alto 2, Vega Baja, are part of a group of six wells that were sampled for pesticides. The wells had been drilled to study nitrate contamination near pineapple fields [5]. Pineapples were grown in the area for many years but by 2008 production had stopped. The herbicide Bromacil was detected in all six wells with the highest level, of 30 µg/L, at Hill 2 in February 1997 [6].

The United States Environmental Protection Agency has classified the most contaminated sites in the United States and its territories in the National Priority List, better known as “Superfund” sites. Puerto Rico has 16 sites of which 8 involve contaminated groundwater. [2] looked at three of these sites and demonstrated that the benefits of remediation exceed the costs.

High frequency groundwater temperature data are the unintended free byproduct of the switch from floats to pressure transducers. Globally, many hydrologic agencies have switched to pressure transducers and probably have large amounts of unused groundwater temperature data. In the case of the USGS-CFWSC in Puerto Rico, the data frequency is hourly. This study will determine if, in a tropical environment the groundwater temperature data can be used to identify areas at high risk from superficial contaminants. A tropical environment with a reduced annual and diurnal air temperature cycles simplifies some aspects of this work.

This study will look at the correlation between depth-to-water and water temperature in observation wells. The hypothesis is that the average Pearson correlation coefficient between depth-to-water and water temperature for the observation wells in the karst upper unit of the NCL aquifer will be higher than in the observation wells in the alluvial SCP aquifer. If this hypothesis is correct, then the karst upper unit of the NCL aquifer as a whole is at greater risk from superficial contaminants than the alluvial SCP aquifer. The null hypothesis is that the average Pearson correlation coefficient in the karst upper unit of the NCL is not significantly different than the alluvial SCP aquifer. If the null hypothesis cannot be rejected then it would mean that, in terms of intrinsic vulnerability, there are no significant differences between the upper unit of the NCL and the SCP aquifer. The hypothesis will fail if the ratio of intra-aquifer to inter-aquifer differences is large. Either result is useful to improve the management of groundwater resources in Puerto Rico. In terms of aquifer vulnerability it is important to know if the upper unit of the NCL is one unit or needs to be managed on a smaller length scale. The hypothesis applies to stations were the water level is controlled by rainfall and not tides nor the cycling of production wells.

The hypothesis of this part of the study is that the Pearson correlation coefficient between the depth-to-water and the water temperature will be higher in the upper unit of the NCL than in the SCP. If the hypothesis is valid then it means that the upper unit of the NCL aquifer as a whole is at greater risk from superficial contamination than the SCP aquifer. The hypothesis will not be valid if the intra-aquifer variability is large relative to the inter-aquifer variability.

3. Methods

Two methods were used to identify areas in Puerto Rico that are at higher risk from superficial contamination than other areas. At 33 non-pumping observations wells operated by the United States Geological Survey (USGS) hourly data were used to calculate the correlation between depth-to-water and water temperature. At each station the time period was between 12 and 18 months. If available, data from 2005 were used as this was a period when many observation wells were at record highs. The idea is that those stations with the highest correlation were those at the highest risk. This applies only to stations where the water level in the observation well is controlled by rainfall and not tides or the pumping schedule of nearby production wells.

As of May 2015, the 33 stations used in this study have been visited by USGS-CFWSC employees 5317 times. The complete data for each station are in Appendix I. The daily and monthly water level data, and metadata such as location and well depth, are available on the Internet [41]. The hourly data, both water level and water temperature, are unpublished.

The USGS has one observation well, Florida 7, Florida, in the North Coast Limestone that also has a rain gage. At this site the minimum rainfall needed to raise the water level in the well and the lag time between rainfall and water level rise were calculated. Florida 7 is an abandoned production well that is now used as an observation well.

In this study, 39 percent of the observation wells were piezometers that had been drilled by the USGS-CFWSC for scientific studies, 61 percent were abandoned production wells drilled for public supply, agriculture, industry, or an orphanage. About 90 percent of all the production water wells drilled in Puerto Rico are abandoned. Piezometers are designed to obtain data from a specific point in the aquifer, while production wells are designed to maximize production. Compared to piezometers, production wells tend to be larger diameter, deeper, and tend to be open to the aquifer over a larger distance, the construction details of piezometers are better documented than production wells. There are many things about a well that cannot be predicted before its construction. The unknowns include its productivity, its response time to rain events, and what will be the range in water level over time.

If a production well is producing large quantities of clean water, it will not be abandoned and made available to be an observation well. Compared to operating production wells, abandoned production wells tend to have lower hydraulic conductivity or are contaminated. Tiburones, Barceloneta is a production well that was abandoned after it became contaminated with carbon tetrachloride from a nearby spill [13]. The 33 observation wells used in this study range in diameter from 50 to 510 mm, well depth ranges from 6 to 178 m, and average depth-to-water ranges from 0.4 to 127 m.

This study used raw hourly water level and temperature data from 33 non-pumping observation wells located throughout the aquifers of the main island of Puerto Rico. The locations are shown in Figure 1. The upper unit of the NCL, the lower unit of the NCL, SCP, and the rest of Puerto Rico have 12, four, 13, and four stations respectively. Each station has 12 to 18 months of data. Most years have 8760 hours, leap years have 8784. All of the data were collected with DH-21 pressure transducers and are courtesy of the USGS-CFWSC. The use of brand names is for identification purposes only and does not constitute endorsement by the Universidad del Turabo. During bimonthly site visits, the water levels calculated by the pressure transducer were compared to the water levels measured independently. At the office, the raw data are subject to several corrections, and the noon values are published. These corrections will not change the correlations presented here.

Using a p-value of 0.05 and a sample size of 250, a Pearson correlation coefficient of around 0.12 is significant. When the sample size reaches 10,000, a Pearson correlation coefficient of 0.02 is significant. With large sample sizes even relationships with very low correlation can be significant.

4. Results

The data about the observation wells used in the study of the correlation between the depth-to-water and the water temperature. One observation well in Salinas in the SCP was eliminated from the study because the water level is controlled by tides and the pumping schedule of nearby production wells. The four stations with the highest correlations between the depth-to-water and water temperature are in the upper unit of the NCL aquifer. The station Cbgar in Quebradillas has a correlation between the depth-to-water and the water temperature of 0.99 which is the highest of the 32 observation wells in the study. The data from Cbgar are shown in Figure 2. An example of an observation well with no correlation between depth-to-water and water temperature is Maguayo 2 in Dorado and the data are shown in Figure 3.

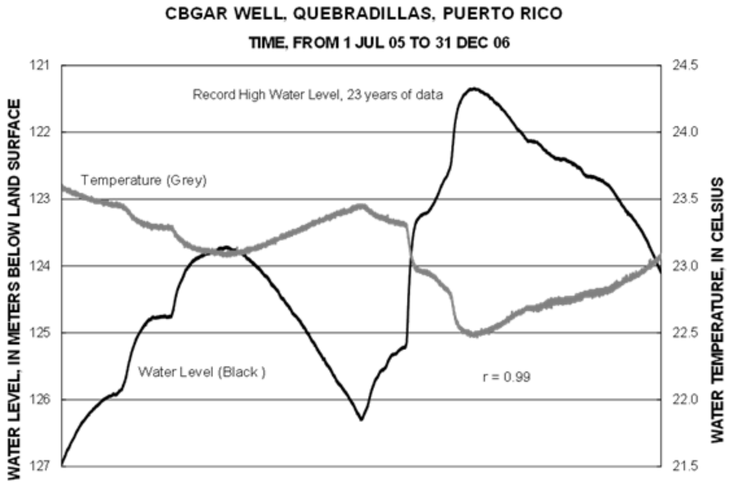

Figure 2. The hourly water level (black) and water temperature (grey) of the Cbgar observation well in Quebradillas, Puerto Rico from 1 July 2005 to 31 December 2006. This is station with the highest correlation between depth-to-water and water temperature of the 32 stations in the study. Data courtesy of the USGS

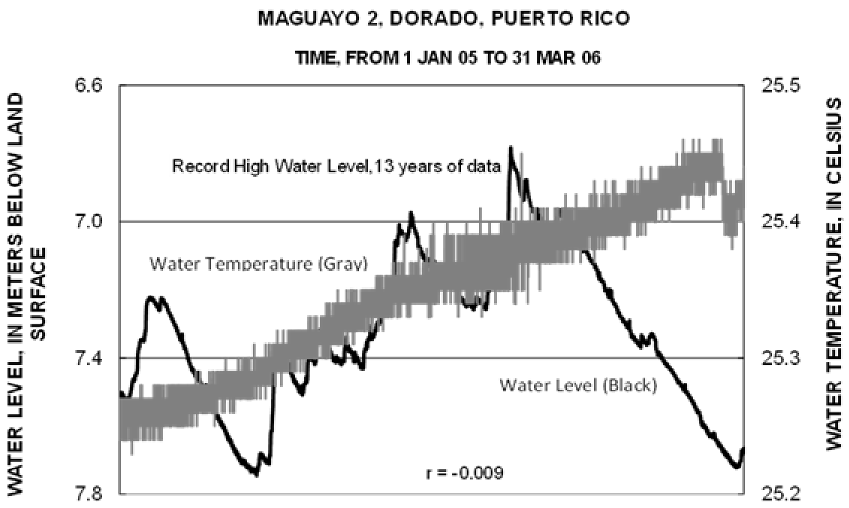

Figure 3. The hourly water level (black) and water temperature (grey) of the Maguayo 2 observation well in Dorado, Puerto Rico from 1 January 2005 to 31 March 2006. This is an example of a station with no correlation between depth-to-water and water temperature. Data courtesy of the USGS

The average Pearson correlation coefficient between the depth-to-water and the water temperature in the upper unit of the NCL aquifer is 0.29 with a standard deviation of 0.62 versus 0.01 and 0.50 in the SCP aquifer. The p-value is 0.25. This means that the upper unit of the NCL aquifer as a whole is not at higher risk from superficial contamination. Rather than treat the entire unit as being at-risk the NCL aquifer needs to be broken up into smaller at-risk units.

The two stations with the highest correlations between the depth-to-water and water temperature are in Quebradillas and the adjoining municipio of Camuy. In Puerto Rico the municipio is the equivalent of county in United States. The two stations with the third and fourth highest correlation between the depth-to-water and water temperature are in the adjoining municipios of Manatí and Vega Baja. All four municipios are in the central part of the north coast and are the two regions with the lowest travel times between rainfall and aquifer recharge. The two at-risk areas are about 50 km apart and are separated by two rivers.

The Florida 7 observation well in Florida has a rain gage at the wellhead. This observation well is in the lower unit of the NCL aquifer. At times, during the rainy season, the water level in the well goes up every day with the afternoon rain storm. This pattern has seldom been observed and indicates a better connection with the surface than most observation wells. The water level in the observation well goes up with as little as five millimeters of rain and in less than three hours. There are no water temperature data at this station. The relationship between rainfall and the rise in water level is shown in Figure 4.

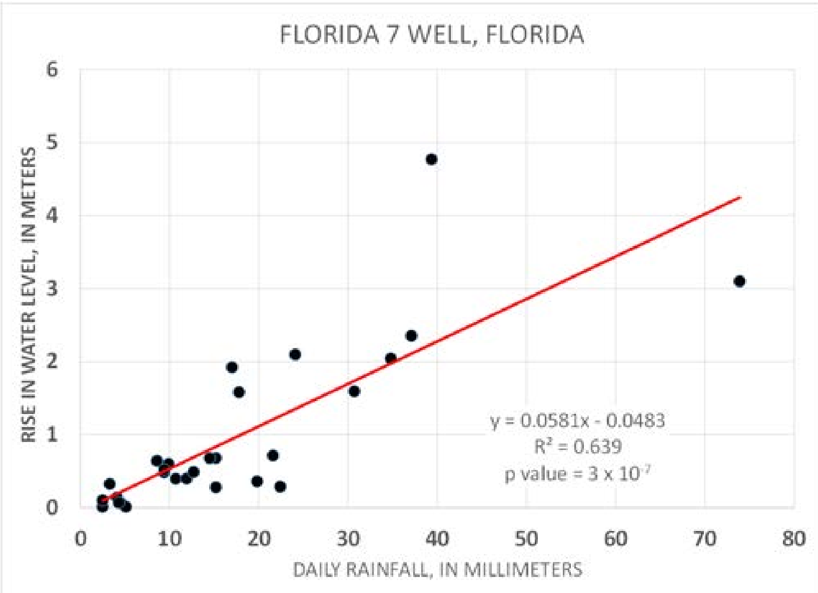

Figure 4. Rise in water level versus rainfall at the Florida 7 well, Florida. Data courtesy of USGS

The three regions with the shortest travel time between rainfall and aquifer recharge are Quebradillas/Camuy, Manatí/Vega Baja, and Florida. The locations of these three areas are shown in Figure 1. These three areas are at the highest risk of the rapid movement of superficial contamination.

5. A Proposed Experiment

Using data from non-pumping observation wells, three areas in the NCL aquifer were identified that are at higher risk from superficial contamination than either the rest of the NCL aquifer or other aquifers in Puerto Rico. After a heavy rainstorm, it is probable that in these three areas that the rainwater recharges the aquifer in less than 24 hours. The following proposed experiment will for the first time measure the travel time between rainfall and aquifer recharge in Puerto Rico.

In the three identified areas there are production water wells. Most production water wells in Puerto Rico are owned and operated by the Puerto Rico Aqueducts and Sewer Authority (PRASA). If electronic sensors were installed to measure the temperature and specific conductance of the water pumped out of the well, then the hypothesis of this proposed experiment is that both variables will drop within 24 hours of a heavy rainfall event. At the wellhead the instrumentation will include a rain gage and sensors to measure the temperature and specific conductance of the rainwater. The amount, temperature, and specific conductance of rainwater are useful to understand what fraction of the pumped water is recent recharge water versus old aquifer water.

Figure 5 has synthetic data and shows what will happen to the pumped water if the old aquifer water has a temperature of 26 °C and a specific conductance 500 µS/cm. In the scenario the rainwater has a temperature of 22°C and a specific conductance of 50 µS/cm, the first recharge water reaches the pumping well four hours after the rainfall and by seven hours the pumped water is 20 percent new and 80 percent old water. At that mixture the production water has a temperature of 25.2 °C and a specific conductance of 510 µS/cm.

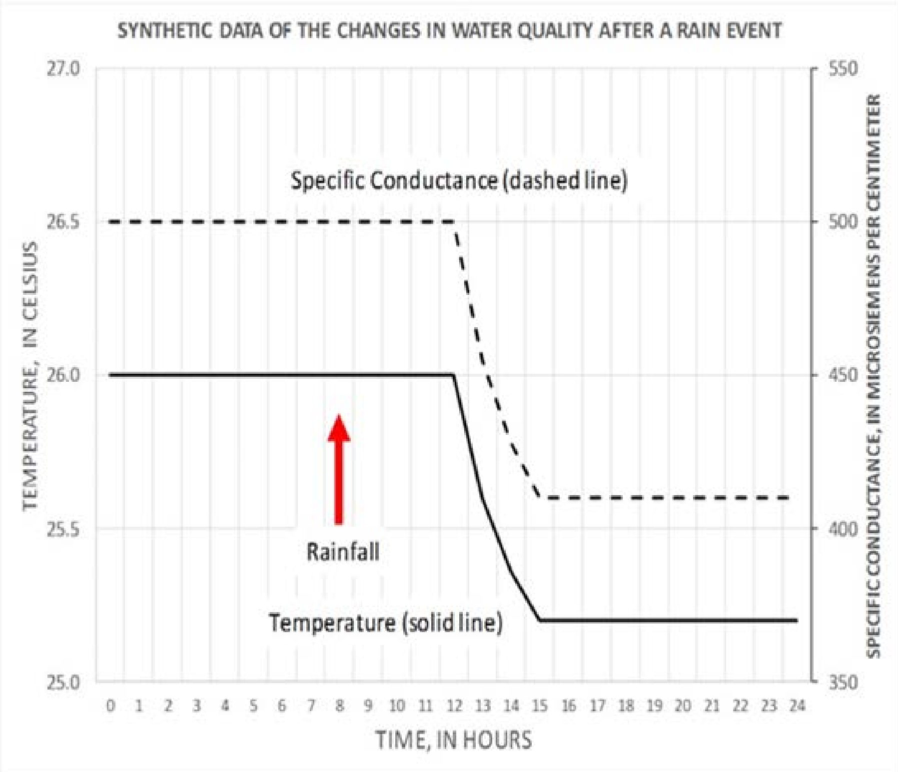

Figure 5. Synthetic data and shows what will happen to the pumped water if the old aquifer water has a temperature of 26 °C and a specific conductance 500 µS/cm

6. Discussion

The idea of the experiment is to measure the travel time between rainfall and aquifer recharge in the identified high-risk areas. The hypothesis is that the new recharge water will arrive at the production well in less than 24 hours and when this happens that both the temperature and the specific conductance of the water will decline. It will also be interesting to see how long after an isolated rain event it will take the water temperature and specific conductance to return to the pre-event values. Time-series specific conductance data have never been used to study groundwater in Puerto Rico. After a rain event, it is probable that the water temperature will return to normal faster than the specific conductance. It takes longer for ions like calcite to enter solution than it does for temperature to reach equilibrium. One goal of this experiment is to better understand the time scale of which specific conductance data can be used to measure travel time between the rain event and aquifer recharge.

It is important to publish the results of the study of the correlation between the depth-to-water and water temperature because it provides useful information to water resources managers. Traditional the karst NCL aquifer has been viewed as being uniformly at risk. This study documents that Quebradillas/Camuy, Manatí/Vega Baja, and Florida are at higher risk than either the non-karst aquifers or the rest of the NCL aquifer. These three areas should receive the highest levels of attention to prevent superficial contamination.

The Cbgar, Quebradillas and Zanja 4, Camuy stations are both highly correlated. They are about 7.4 km apart and they have different connections to the surface. In 18 months Cbgar had six events that caused the water level to rise, while Zanja 4 had 26. Near Zanja 4 there are two production wells, Zanja 2 and Zanja 3, which combined pump 31 liters per second [39]. Both at-risk areas are rolling terrain with no surface drainage. The Quebradillas-Camuy area was traditionally dairy farms, and the Manatí-Vega Baja area had pineapple production, but because of access to good highways, housing construction has increased in both areas in recent years.

It is too late to protect the aquifer in Manatí-Vega Baja. Both Hill 2 and Palo Alto 2 were drilled by the USGS-CFWSC to study nitrate contamination. The source of the nitrates was the fertilizer that was used on the now-abandoned pineapple fields [5]. Hill 2 sits about 10 m from an ephemeral channel that terminates in a nearby sinkhole. At both of these observation wells, the correlation between depth-to-water and water temperature is higher in large rain events than in small rain events. In addition to the nitrate contamination, between the two observation wells there is an abandoned pesticide warehouse that has been added to the Superfund list [25]. A description of the pesticide warehouse as having a “semi-confined aquifer” [25] is in conflict with this study, which finds that it is one of the most vulnerable areas in Puerto Rico. The groundwater flow in this area was modeled by [3] and there is no correlation between the high risk area and a zone of high transmissivity identified in the modeling study. The utility of the methodology of this study is demonstrated by the fact that by studying the physics of the aquifer, areas with high intrinsic vulnerability can be identified. One of the two highest at-risk areas is already contaminated and this confirms the validity of the technique.

Improved knowledge of the travel time between rainfall and aquifer recharge will improve the management of groundwater resources in Puerto Rico. Gasoline is the most commonly transported hazardous material [42]. If during a rainstorm a gasoline truck has an accident and spills its load then these are the areas where the contaminant will reach the aquifer the fastest and thus the areas where the pumps on production water wells need to be turned off the fastest.

7. Conclusion

This study is passive in the sense that no new data were collected. Instead existing data are analyzed to better understand the physical properties of the aquifers of Puerto Rico to identify three areas where the travel time from rainfall to aquifer recharge is less than normal. This study uses hourly data from non-pumping observation wells operated by the USGS-CFWSC to look at the correlation between depth-to-water and water temperature. The idea is that rain is cold and this correlation can be used to identify areas with shorter travel times. A second technique is the use the rainfall and water level data from an observation well in Florida to study an area where the rainfall rapidly causes the water level in the well to rapidly rise.

The logical extension to the passive nature of this study is a proposed experiment to measure the amount of rainfall and the temperature and specific conductance both of the rainfall and in the water pumped from a production well. The hypothesis of the proposed experiment is that in the high-risk areas, both temperature and specific conductance will drop within 24 hours of a rain event. The existing data were used to identify the high-risk areas and the experiment will confirm the validity of this technique. This experiment will be the first to measure the travel time between the rainfall and the aquifer recharge. This experiment will produce information that will improve the management of groundwater resources in Puerto Rico.

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