INTEGRATING GROUNDWATER RESOURCES IN EXISTING WATER SUPPLY INFRASTRUCTURE USING SPATIAL TOOLS

By

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Abstract

Management and development of groundwater resources introduces the challenge of collecting necessary information to understand the system. The information must integrate the aquifer system characteristics and the limitations of the system to avoid a future depletion of this important water resource. Considering the complexity of the system and the amount of information required for the analysis, computational tools and technologies must be developed and applied to collect and integrate information for an effective and efficient assessment of the area of study. This study develops tools and methods for intelligent design, development, and management of groundwater resources in areas with existing, but deficient water infrastructure.

Using Geographic Information System (GIS) technologies, this study integrates water use with the physical, hydraulic, and hydrogeologic characteristics and constraints with water-supply infrastructure systems for development of groundwater systems in a cost-effective manner without causing depletion of the groundwater resources. The technologies are applied to the hydrogeophysical system at University of Puerto Rico at Mayagüez (UPRM), which served as the validation site. The preparation of a groundwater assessment and development plan for this site not only serves as an application site for this research and provides a guide for proper water management of the site that leads to benefits of large impacts to the institution and society as a whole.

Results show that the method and tools developed serves as an effective technology to assess the feasibility of using groundwater resources in an area with existing water supply infrastructure. The GIS method applied to the UPRM site provided tools to characterize the groundwater system, estimate groundwater extraction rates subjected to system constraints, and design an optimize well field to supply a given water if the site. Results indicate that the groundwater system in the validation site defines as a confined aquifer with average transmissitivity and storage of 219 m^2/day (79,935 m^3/yr) and 0.003, respectively. A total of 2 well pumping at 325 m^3/day (118,625 m^3/yr) per well would be required to supply a water use of 570.9 m^3/day (208,379 m^3/yr). This rate and well field design minimize aquifer drawdown and depletion and optimize cost of development. It is concluded that groundwater resources may be used to supply

the present water use of UPRM without causing an overexploitation to the aquifer. Furthermore, the GIS tools provide an alternative to visualize the results and less time consume in managing the data.

Resumen

El manejo y desarrollo de aguas subterráneas conlleva retos en la colección de información que permita entender el sistema. La información colectada tiene que incluir las características del acuífero y las limitaciones del sistema para evitar la sobre explotación de este importante recurso de agua. Debido a la complejidad de los sistemas de aguas subterráneas y la cantidad de información envuelta en los análisis computacionales, nuevas tecnologías deben desarrollarse y aplicarse para colectar e integrar información para una evaluación efectiva y eficiente del área de estudio. Este estudio desarrolla herramientas y métodos para un diseño inteligente, el manejo y desarrollo del recurso de aguas subterráneas en áreas de estudio donde pueda haber una infraestructura existente pero que no esté operando de manera eficiente.

Utilizando Sistemas de Información Geográfica (SIG), este estudio integra la demanda de agua potable, las características físicas, hidrogeológicas, hidráulicas y las restricciones que tiene la infraestructura del sistema de distribución de agua para desarrollar el recurso de aguas subterráneas de manera costo efectivo y sin causar un agotamiento del recurso por sobreexplotación. Las tecnologías son aplicadas al sistema hidrogeofísico de la Universidad de Puerto Rico Recinto de Mayagüez (UPRM) el cual fue utilizado como caso de validación. La preparación de un plan para la evaluación y desarrollo del recurso de aguas subterráneas en este sitio, sirve como herramienta de aplicación para esta investigación y provee guía para el manejo apropiado de agua que beneficia a la institución y la sociedad en general.

Los resultados muestran que los métodos y herramientas desarrollados son una tecnología efectiva para evaluar la viabilidad de usar aguas subterráneas en un área con un sistema de distribución de agua existente. El método de SIG aplicado a la UPRM provee herramientas para caracterizar el sistema de aguas subterráneas, estimar la taza de extracción sujeta a restricciones del sistema, y diseñar y optimizar un campo de pozos para suplir una demanda dada de agua para el área de estudio. Los resultados indican que el agua subterránea en el sitio de validación se comporta como acuífero confinado con un promedio de transmisividad y coeficiente de almacenamiento de 219 m^3/día (79,935 m^3/día) y 0.003, respectivamente. Un total de 2 pozos, bombeando a 325 m^3/día (118,625 m^3/día) por pozos se requerirían para suplir una demanda de

570.9 m^3/día (208,379 m^3//año). Estas tazas de extracción y diseño de campo de pozos, minimiza el abatimiento y agotamiento del acuífero y optimiza el costo de desarrollo. Se concluye que los recursos de aguas subterráneas pueden suplir la demanda presente de UPRM sin causar sobreexplotación del acuífero. Además, la herramienta SIG proveyó una alternativa para la visualización de resultados y manejo de data de manera más rápida.

Acknowledgments

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1. Introduction

The water resource is one of the most important resources in life. Its availability impacts significantly the socioeconomic development of a region (UNECA, 2012). High population growth, industrial advancement, and urban development have resulted in a high demand of water that brings the need for adequate management of this precious resource (Asano and Cotruvo, 2004). Many water issues arise from inadequate water supply, improper water management, and widespread contamination problems (Storch, 2004). The use of groundwater for water supply has many advantages over surface water systems (Wright, 2009). For instance, groundwater systems have a large storage volume, and impart low environmental impacts if the system is managed adequately. In addition, a relatively large area of aquifers, offers less limitations in regards to the location of the water intake.

Proper development and planning of groundwater resources requires collecting, integrating, and applying large amounts of information. In many cases, the management and development of groundwater resources introduces the challenge of gathering a large amount of necessary information to understand the system (Watkins et al., 1996). The lack of information may result in affecting some components of the system analysis such as the water replenishment in the aquifers, groundwater pollution, and well design. To deal with these problems, there is a need to implement sustainable technologies that handles the groundwater resources based on the watershed issues (Uhl et al., 2009). This requires better understanding and integration of aquifer recharge and extractions, as well as groundwater contamination. It also requires implementing a sustainable consumption plan to manage groundwater abstractions (Storch, 2004).

The understanding and analysis of groundwater resources is complex and requires combining multidisciplinary knowledge including geologic, hydrologic, and socioeconomic data (Martin et al., 2005). There are a broad of technologies and models that have been developed in order to analyze and characterize groundwater systems. Geographic Information System is a useful tool which empowers the gathering of spatial information to perform intelligent and integrated groundwater development (Martin et al. 2005).

Development of groundwater resources for areas with existing water infrastructure is beneficial if: (1) there is not enough water to supply the demand; (2) system inefficiencies results in inadequate water supply service; and/or (3) the cost of water supply is much higher than the cost of using groundwater. The technologies are applied to the hydrogeophysical system at University of Puerto Rico at Mayagüez (UPRM), which served as the validation site. The preparation of a groundwater assessment and development plan for this site serves as an application site for this research, and also provides a guide for proper water management of the site. This will lead to benefits of large impacts to the institution and society as a whole.

1.1. Objectives

This research aims at developing tools and methods for intelligent design, development, and management of groundwater resources in areas with existing, but inefficient water infrastructure. The tools and methods rely on GIS technologies to integrate water use with the physical, hydrological, groundwater hydraulic characteristics, and constraints of the hydrogeological and water-supply infrastructure systems. The developed tools and methods are applied to the hydrogeophysical system at UPRM campus as a case study and application site. Specifically, this work:

- Develops a site-specific model for groundwater development using GIS technologies
    - characterizes the groundwater systems and determine parameters necessary to describe the system
    - determines the specific capacity and general aspects for the design of the pumping well(s)
    - determines the water use of the desired project
    - identifies and quantifies system constraints
- Integrates groundwater system parameters, study-area infrastructure, and well-field design, within a framework of system constraints.

- Develops a method-based model in GIS to provide tools for cost-effective groundwater resource planning, development, and management.

1.2. Research Significances

There is great need to properly develop and manage groundwater resources at the local and regional level. Several tools have been developed to assess spatial characteristics of groundwater systems, including: GIS technologies, numerical models; aquifer and well performance methods; water budget estimation; and water quality assessment. The body of state-of-the-art knowledge and techniques on these tools is discussed in the literature review (chapter 2) of this document. These tools have been applied individually and have not been integrated at levels subjected to system constraints. Using Geographic Information System (GIS) technologies, this study integrates water use with the physical, hydraulic, and hydrogeologic characteristics and constraints with water-supply infrastructure systems for development of groundwater systems in a cost-effective manner without causing depletion of the groundwater resources. The development of a Hydrogeological-Water Use Model using GSI provides an efficient tool for intelligent design, development, and management of groundwater resources. Because GIS is a simple tool, the model can be used by planners and water resources and environmental managers as a quick alternative to determining the feasibility of using the groundwater resources integrated with existing infrastructure as a water supply system.

2. Literature Review

Groundwater resources are an important source of fresh water for human consumption and other uses, and represent 30.1 % of the total usable freshwater in the planet (United Nations Water, 2012). In Puerto Rico, groundwater supplies up to 20 percent of the total water use (Molina and Gómez, 2008).

During the past decades, population and industrialization have increased and resulted in exploitation and depletion of groundwater resources (Villholth, 2005). Adequate management, planning, use, and development of groundwater resources require knowledge of the particular characteristics of the area of interest. Studies suggest that one of the reasons for aquifer depletion, seawater intrusion, and contamination is the lack of knowledge on criteria and characteristics that must be considered prior to water extraction from a groundwater system (Villholth, 2005). This problem is further amplified by the complexities and inadequate sensory perception (difficult to visualize, hear, touch, measure and others) of groundwater systems. This chapter provides a literature review of the aspects that may be useful when performing a groundwater resources development and planning.

2.1. Groundwater Management Needs

Inadequate water management over decades has resulted in the contamination and overexploitation of the water resources (Storch, 2004). Warnings of groundwater crisis had led to calls for urgent management responses that require translating broad macro generalizations into specific management response (FAO, 2003). These responses must be addressed within specific contexts of the hydrologeological, hydrodynamic and human use settings. Groundwater management should therefore take place at localized scales (FAO, 2003)

The largely unseen nature of groundwater has resulted in the development initiatives that do not consider the hydrodynamic limits of the resource for proper pattern of abstraction (FAO, 2003). Storch (2004) suggest that adequate management of groundwater resources requires the implementation of a continuous improvement plan for groundwater extraction protection. This plan must be based on the particular hydrogeologic, hydraulic, and water quality properties of the groundwater system. This information must be integrated with the hydrologic conditions in a spatial and temporal context to assess the best management practices of the system. Accuracy of the results depends of the quality of the data and the conceptual model of the system (Watkins et al., 1996). Integration of the data within the conceptual model requires adequate tools that can assemble multiple layers of information and produce definite management outcomes.

2.2. Geographic Information Systems (GIS) for Water Management

GIS is a computational tool, which combines hardware, software, and data management that represents information geographically referenced (Watkins et al., 1996). GIS has taken an important role in the development of groundwater resources during the past years because of its ability of work with spatial and temporal data (Mane et al., 2007) and its ability to integrate a large number of data sets within a georeferenced conceptual model. GIS can be used to gather information of rainfall, evapotranspiration, soil crops, topography, hydrologic features, geology and delineate aquifer geometry, hydrogeologic properties, aquifer recharge, groundwater contamination and other system characteristics useful for making decisions on groundwater development and management (Martin et al., 2005).

GIS has also been used to feed spatial data for development of numerical groundwater models (Watkins et al., 1996). The developments of numerical groundwater models are complex and require a high level of expertise and knowledge. The amount of data and time and effort required for model development and understanding may result in substantial cost. This precludes many environmental managers and planners from applying these models as management and decision making tools (Sulin and Wenbin, 2009).

GIS is a simple tool used by many water resources and environmental managers as well as planners (Martin et al., 2005). It provides applications related to planning, design, maintenance, operations and analysis in the water resources field. The capability of incorporating water resource information as a spatial database helps for an easy visualization of the area of study (Kljucanin et al. 2010). GIS tools serve for spatial data and non-spatial management providing more reliable results (Watkins et al., 1996), and can assist with waste management, hydrological modeling, water supply design, as well as groundwater resource planning. It permits to store the data using different formats such as text, diagram, or maps. It also has the capability of showing results according to the user need (maps, tables, documents and others) (Kljucanin et al., 2010). The GIS software is commonly provided by ESRI (2012). As a water management tool, GIS provides a centralized database tool which can be accessed by different private or government offices providing the same data source. This helps in the decision making process and provides coherent results (Pierre and Musy, 1997).

Hill et al. (2005) used GIS tools to look for the suitability of wells as water intake. His work established constrains criteria according to the depth of aquifer, bedrock characteristics and other criteria which served to determine potential areas in Peoria City, Arizona for groundwater development. The GIS analysis was performed assigning weights and ranks to the criteria and was applied to develop a spatial database of the suitable places for wells construction. GIS has also been used to develop planning tools for protection, development, and management (Martin et al., 2005) of groundwater resources. The planning process incorporates, among several other aspects, groundwater recharge, water quality, capture zones, surface-/ground-water interactions, and potential contaminants sources. These studies indicate that there is a need to develop tools and methods that incorporate the use of GIS technologies for proper development of groundwater resources. These tools and methods must integrate water resources data, system parameters, and strategies to attain project-specific objectives and constraints. Attending this needs ESRI have worked during recent years in the development of tools to visualize, and analyze hydrogeologic data and support groundwater analysis and modeling (ESRI, 2011). ArcGIS, which is an integration of GIS software products,(ESRI, 2012), in combination with ArcHydro tool allow the creation of water levels and water quality maps, and aquifer maps. It also allows visualization of borehole logs and integration of MODFLOW® models (Yang et al., 2010).

GIS technologies have also been applied to assess and develop surface water resources, transportation, geotechnical, electrical, and other infrastructure systems (Player, 2000). GIS has been applied to collect and analyze spatial data, such as: land condition, existing water network, proposed water network, and pipelines characteristics (pressures, length material, diameter), all of which are required for making efficient analysis of the water distribution system (Wang et al., 2008a). Player (2000) used GIS tools to perform a site investigation which identifies geotechnical problems such as weak soil, unstable slope and geologic hazards in Ottumwa Bypass, Iowa. The study showed the importance and benefit of using GIS for collecting information such as soil survey, topography maps, road network that later were used for determine the potential geotechnical problems that affect the design of transportation systems. For most of these analyses, the most common GIS application used is the *Network Analyst* (Player, 2000), which serves to model and analyze the water, railroad, gas and communication transportation. This tool provides a manner to represent the input data, modeling the transportation of an element (gas, road, electricity and water), and visualizes the output (utilities maps, highway maps, others). Similar to *Network Analyst*, GIS has other tools that permit management of a variety of data.

2.3. Characteristics of Groundwater Systems

Accurate analysis of groundwater resources needs adequate description of the groundwater system, and including the aquifer and wells hydraulic characteristics. The hydraulic properties of aquifers describe the behavior of the system after injection or extraction stressors, and depend on the type of aquifer (confined, unconfined, and/or leaky) in the study area (Subrahmanyam and Khan, 2008). Hydraulic and aquifer characteristics include the geologic character, aquifer thickness and depth, and hydraulic parameters such as transmissivity, hydraulic conductivity, and storage coefficient of the aquifer.

2.3.1. Aquifer Test

Aquifer characteristics are commonly obtained from soil and geologic borings, road cuts and geophysical methods (Abrams, 2010). Hydraulic properties are commonly estimated from aquifer tests, which consist of pumping water at a constant rate while measuring the water levels and drawdown at different time intervals in the pumping well and observation wells (Sakr, 2001).

Unsteady aquifer test data is typically analyzed using equations for radial flow in groundwater, as those developed by Theis (Jacob, 1947) for confined aquifer, Hantush-Jacob for semi-confined aquifers, and Newman for unconfined aquifer (Kruseman and Ridder, 1994). The Theis method equation is described by:

$$s = \frac{Q}{4 * \pi * T} W(u) \qquad (1)$$

and

$$u = \frac{r^2 * S}{4 * T * t} \qquad (2)$$

where:
s= drawdown [length],
T = transmissivity [length^2 / time],
Q= flow from the pimping well [volume/time],
W(u)= well function for confined aquifers,
π = 3.14,
u = series value obtained from the type curve,
S = storage coefficient, and
r = distance between the pumping well and the corresponding observation well [length].

The Hantush-Jacob method applies a similar equation, but with a different *Well Function,* for leaky confined aquifers (Todd and Mays, 2005). The *Well Function* for the leaky confined aquifer (W(u ,B)) considers the thickness and vertical hydraulic conductivity of the semi-confining unit. Equations developed for the unconfined aquifer consider the vertical hydraulic conductivity and the specific yield of the unconfined aquifer. The *Well Function* for the different type of aquifers are represented by different type curves. Equation 2 can be applied with the different *Well Functions* and the representative *Type Curves* (as shown in Figure 1) drawdown response during aquifer tests to determine the hydraulic properties and type of aquifer.

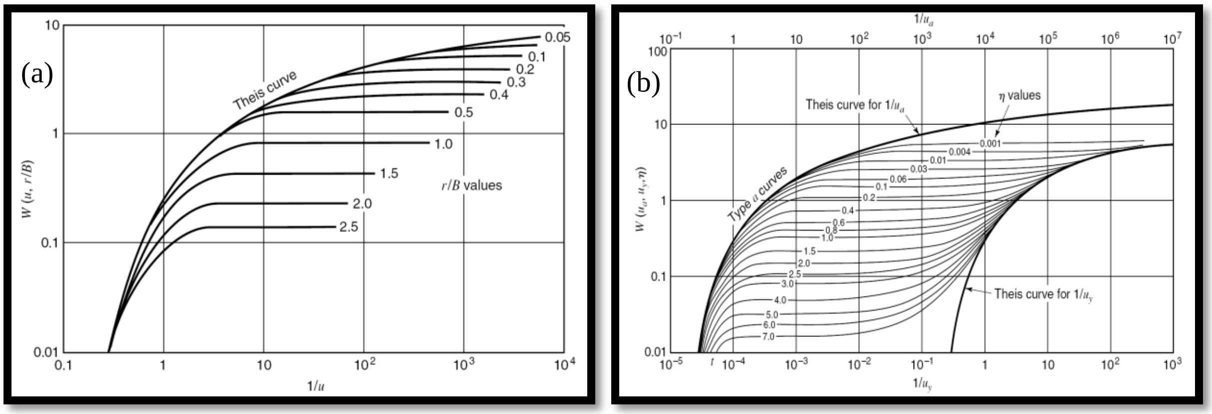


Figure 1: a) Type Curve for leaky and unconfined aquifer analysis, b) Type Curves for unconfined aquifer analysis (Mays, 2005)

All of the methods disputed for the analysis of unsteady drawdown data are constrained by the following assumptions (Kruseman,1994):

- aquifer has an infinite extent,
- aquifer is homogenous characteristics, is isotropic and uniformed in its thickness over the area that is under test,
- piezometric surface around the area that is influenced by the test is horizontal prior to pumping,
- discharge rate is constant along the test,
- wells involved in the test are completely penetrating the aquifer thickness, and are subjected to horizontal flow,
- storage in the well is neglected, and
- water extracted from the storage aquifer is discharged instantaneously during the decline of hydraulic heads.

The following are assumptions considered when the type of aquifer is a leaky aquifer (Trinchero et al., 2008)

- aquitard has an infinite extent,
- flow in the aquitard is vertical, and
- drawdown in the aquitard is negligible.

Aquifer test data may also be analyzed using linearized forms of the radial flow equations. Linearization of the radial flow equation for confined aquifers (equations 1 and 2) for values of $\mu < 0.05$ (Alexander and Saar, 2011) yields a semi-logarithmic relation between time and drawdown:

$$s = \frac{2.3Q}{4 * \pi * T} \log\left(\frac{2.25Tt}{sr^2}\right) \tag{3}$$

In this linearized form, a semi-logarithmic plot of the drawdown (Figure 2) yields a straight line for confined systems (Cooper-Jacob method). The change in drawdown (Δs) over a log cycle (slope of the regression line) for a given discharge (Q), π = 3.14 and distance from pumping well (r) and the time intercept at s = 0 (t_0) are used to calculated transmissivity (T) and storage coefficients (S):

$$T = \frac{2.3Q}{4 * \prod \Delta s} \tag{4}$$

$$S = \frac{2.25Tt_0}{r^2} \tag{5}$$

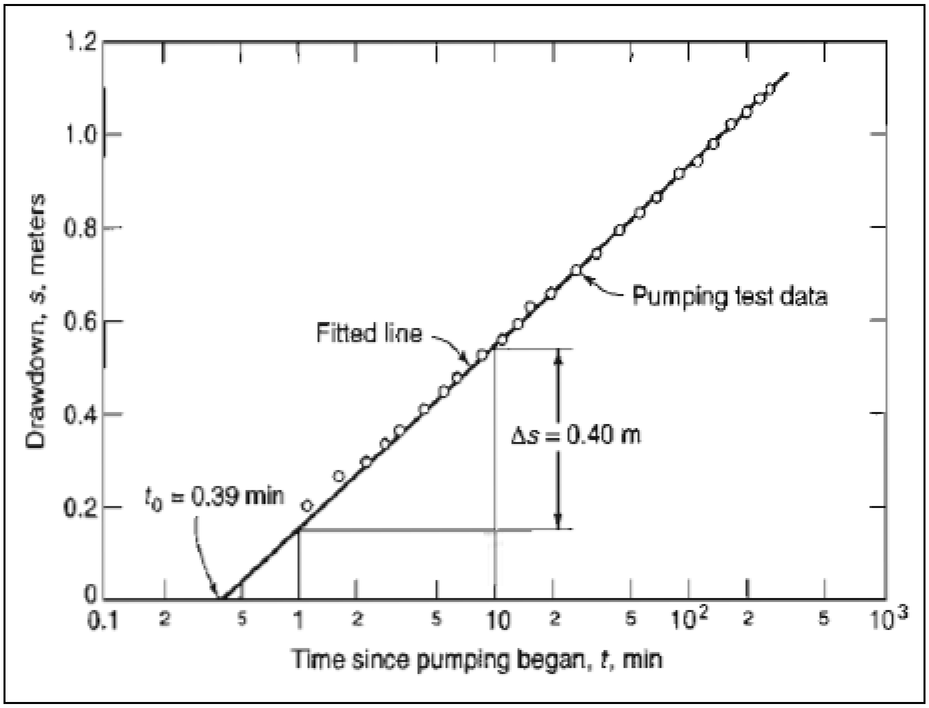


Figure 2: Example of Cooper-Jacob method solution (Todd and Mays, 2005)

Alenxander and Saar (2011) applies the linearized form for analyzing drawdown data in a well field looking a higher permitted value for μ (> 0.05). They suggested that increasing the value of μ allowed for using the Jacob method analysis could lead to considering useful data obtained from monitoring wells that are located in a greater distance from the pumping well.

A plot of time vs. drawdown for a leaky aquifer shows a curve with an inflection point. The Hantush inflection point method (Trinchero et al., 2008) can be applied to these data to determine the hydraulic properties of the system. Their study evaluates the hydraulic properties for a leaky aquifer using a double inflection point method and comparing the results with two conventional methods, curve matching approach described by Walton (1962) and the inflection point method (Trinchero et al., 2008). The results show that for homogenous conditions, all methods provided similar results, but when considering the heterogenous conditions in the system, all of the methods provided different results.

For unconfined aquifers, Moench (1994) developed a numerical code using the Newman's model to analyze water-table aquifers. It used published data of three pumping tests and concluded that using Newman's model provided similar results in comparison with water-balance calculations to obtain the specific yield values.

Equations 1 and 2 which may be applied to analyze data from coastal aquifers, but must take into account density differences ratios and the length of the salt-water/fresh-water interface (Sakr, 2001). Development and management of groundwater in coastal areas must take into account the proximity to the salt-/fresh-water interface.

In the case of multiple pumping wells in a particular area, it is necessary to account for the effect of multiple drawdowns. Using the principle of superposition, the total drawdown at a distance r (ST(r)) is calculated as the sum of the individual drawdowns (SR(r)):

$$ST = \sum SR(r) \tag{6}$$

where:
ST = total drawdown [length], and
Sr = drawdown caused by each well located a at distance r to the point of interest on the observation well [length].

MacMillan (2009) on his study performed modifications to the Theis equation to provide a analytical method to determine the size and spacing of a well network needed to comply the water use. This study applied the principle of superposition to describe the total drawdown from the well field at any point.

2.4. Well Performance

Development of groundwater extraction strategies from pumping wells must also consider the production capacity of the well(s), design of the well(s), well field, and pumping schedules (Jha et al., 2006). Well design depends on the hydrogeologic settings (lithology, stratigraphy, production zones), the amount of water to be extracted, and the location of the pump. In general, well performance tests are conducted looking to determine the energy losses of the aquifer and well pumped during the test (Avci et al., 2010). A common test known is the step-drawdown test developed by Jacob (1947). It provide information to evaluate aquifer parameters, well(s) losses and well(s) efficiency.

Rorabaugh (1953) proposed a general form for the Jacob method suggesting the empirical estimation of the exponential coefficient of well losses (n) instead of assuming a value equal to 2 (Kawecki, 1995). Avci et al. (2010) proposed an analysis technique to evaluate transient step-drawdown data which is applicable not only to confined systems but also unconfined and non-lineal aquifers. The method consisted into deriving the drawdown relationship respect to the time resulting in more reliable results when compared with other methods described in the study performed by Avci et al. (2010).

2.4.1. Specific Capacity and Step–Drawdown Test

The production capacity of the well can be obtained from specific capacity or step-drawdown tests (Jacob, 1947). These tests involve pumping the well at increasing pumping rates for selected time intervals, while monitoring the drawdown at the extraction well (Alexander and Saar, 2011). The increment in the discharge rate depends on the aquifer characteristics but it should be changed the discharge rate to a next step once equilibrium is reached at the system (Kruseman and Ridder, 1994).

Step-drawdown data is used to establish the relationship between extraction rate (Q) and drawdown (s) at the pumping well and estimate well productivity and efficiency. The relative well productivity is estimated from the specific capacity (SC) of a well, defined as:

$$SC = \frac{Q}{s} \tag{7}$$

Rotzon and El-Kadi (2008) have suggested using the specific capacity for hydraulic properties estimation. Their studies concluded that transmissivity (T) and hydraulic conductivity (K) can correlate to the specific capacity using linear regression in the graphs when the variables have been log-transformed. They focused their studies in Hawaii aquifers and found that the correlations are more accurate when correcting the specific capacity for well losses.

2.4.2. Well Losses and Well Efficiency

The total drawdown (ST) observed in a pumping well depends mainly of two aspects: the aquifer losses (s_a) and the well losses (s_w) as shown in Figure 3. The aquifer losses are described by the laminar flow which results in head losses.

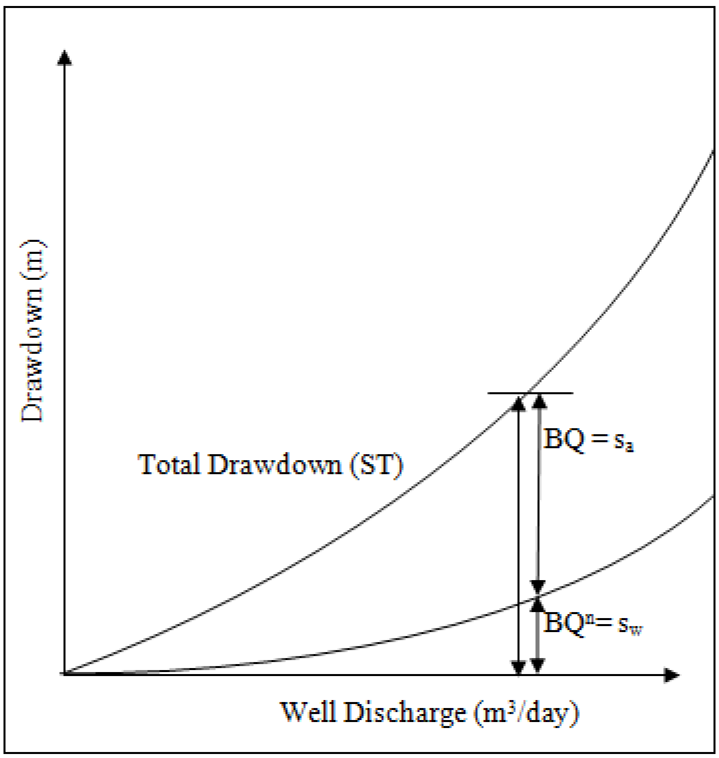


Figure 3: Example showing the head losses involved in the drawdown measure (modified from Todd and Mays, 2005)

The well losses are commonly divided into two losses: linear and non-linear losses. The linear losses are caused by inefficiencies of the well construction and the non-linear losses are caused by the turbulent flow observed in the well screen (Avci et al., 2010). Although most of the methods developed to determine well losses do not consider the linear effect in the well losses in the calculations, there are recognized. Well losses result in a well drawdown that is greater than in the adjacent aquifer.

Step-drawdown test data can also be applied to estimate aquifer and well energy losses (Gianpietro, 2010) according to the following equation:

$$s = BQ + CQ^n \qquad (8)$$

where:
s = drawdown [length],
B= aquifer loss coefficient [time/length^2],
Q = discharge rate [volume/time],
C = well loss coefficient [time/length^2], and
n = exponential coefficient for the well losses .

The *n* coefficient is generally taken equal to 2, but may deviate from this value (Kawecki, 1995). Previous studies suggest values for the n coefficient from 1 to 4 (Avci et al., 2010). For those cases where non-linear behavior is predominating, numerical and graphical solutions have been developed in order to estimate B, C and n coefficient values. Miller and Weber (1983) proposed a quick method in order to determining the well parameters and power value assuming a nonlinear behavior. Their method consisted of an iterative process which assumed that the discharge rate is independent from the loss coefficients.

By relating SC at different Q, equation 9 can be applied to estimate B, C and n coefficient values:

$$\frac{s}{Q} = B + CQ \qquad (9)$$

A plot of Q vs SC (see Figure 4) yields a linear regression for n=2 that can be used to estimate the losses coefficients. There are cases where the regression line does not match exactly the measured values because the assumption of 2 for the *n* value in the equation 9 but 2 it is an accepted for most applications value and commonly used in the practice (Miller and Weber, 1983). Figure 4 shows the relation of the aquifer and well losses to total drawdown data and the plot of equation 9.

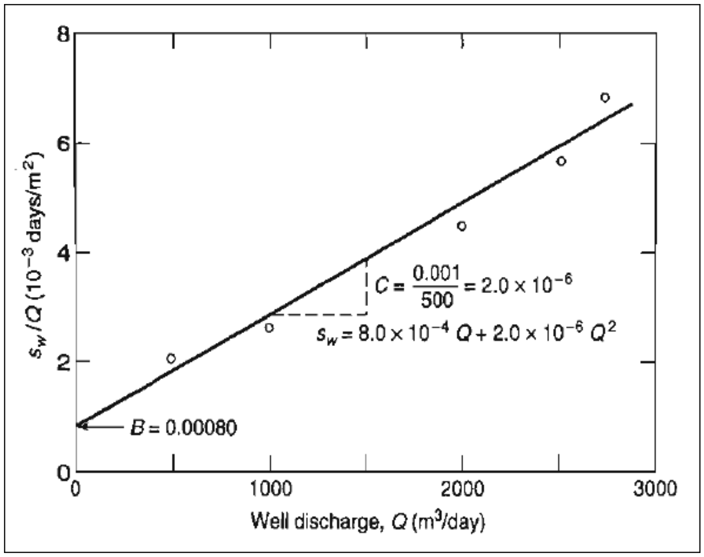


Figure 4: Example showing a 1/SC versus discharge rate curve for the step-drawdown test analysis (Todd and Mays, 2005)

Another way to evaluate the well performance is by calculating the well efficiency (E):

$$E(percent) = \frac{s_{aquifer}}{s_{well}} = \frac{SC_{well}}{SC_{theoretical}} = \frac{BQ}{s_{well}} \quad (10)$$

where $s_{aquifer}$ is the theoretical drawdown at the well, swell is the measured drawdown at the well, SC_{well} and $SC_{theoretical}$ are the measured and theoretical specific capacities, respectively, and C is the aquifer loss coefficient (Equation 8). Even though equation 10 is commonly used for estimating well efficiency, the methods used for determining the theoretical drawdown and measured drawdown may vary according to the system characteristics (Kawecki, 1995).

2.5. Recharge

Sustainable groundwater development requires appropriate estimation of recharge (Manghi et al., 2009). In addition, proper and cost effective groundwater development requires suitable design of wells and well fields, as well as integration of water use and infrastructure, particularly for aquifers of limited extent. The recharge of a groundwater system constitutes its ability to receive water from the surface land once it has passed the unsaturated zone and reached the saturated zone (Betelan and De Smedth, 2007). This is extremely important because recharge limits the amount of water that can be withdrawn from the groundwater system without depleting it. There are different methods to estimates recharge, including the lysimeter, soil-moisture budget, water-table fluctuation, and Darcy methods (Manghi et al., 2009; Silva, 2004; Wright, 2009). The soil budget method has been widely applied to estimate aquifer areas in several regions, but has had limitations in tropical regions (Izuka et al., 2010). Aquifer recharge in these areas is better described by infiltration minus potential evaporation.

The soil-budget, which is a type of hydrological budget method, has been used for recharge estimate (Lee et al., 2007). Its general equation is described by:

$$R = P - E - Ru \tag{11}$$

where:
R = recharge [length/time],
P = precipitation [length/time],
E = evapotranspiration [length/time], and
Ru= surface runoff [length/time].

This relation requires the knowledge of actual evapotranspiration Estimates of actual evapotranspiration can be obtained from equation 12 (Harmsen et al., 2002). Potential evapotranspiration estimates may be determined using the Hargreaves method (Hargreaves and Samani, 1985) (equation 13). For crop coefficient estimates (Kc), FAO (2003) had provided average values as shown on Table 1.

$$Ea = Kc * Ep \tag{12}$$

and

$$Ep = 0.0135 * Rs * Tm \tag{13}$$

where:

Ea = actual evapotranspiration [length/time],
Kc = crop coefficient,
Ep = potential evapotranspiration [length/time],
Rs = solar radiation [length/time], and
Tm = Mean temperature [Celsius].

Table 1: Crop coefficient description (Giovanni, 2007)

No.	Land Use Category	Kc
1	Forest,shrub, woodland and shede	0.85
2	Pasture	0.9
3	Urban and Barren	0.3
4	Agriculture/hay	1
5	Emergent Wetlands	1.2

The Hargreaves method also requires the estimate of the solar radiation which is calculated using the equation 14 and where incoming extraterrestrial radiation values can be obtained using values applicable to Puerto Rico area based on the location and by month of the year (Harmsen et al., 2002).

$$Rs = 0.7 * Ra - b \tag{14}$$

where:
Ra = incoming extraterrestrial radiation (MJ/m^2/day), and
b = empirical constant (4 MJ/m^2/day).

For surface runoff estimates, there are different methods including: rational method and soil conservation service (SCS) method. The SCS method is widely used to estimate runoff for ungauged watershed and small to medium sized watersheds which described by equation 5 in the following (Yu, 1998):

$$Ru = \frac{(P - Ia)^2}{(P - Ia) + So} \tag{15}$$

and

$$S = \frac{1000}{CN} - 10$$

(16)

Where:
Q = direct runoff [length/time],
Ia = initial abstraction (Ia = 0.21*S),
So = potential retention capacity, and
CN = curve number.

Recharge may also be estimated through the development of numerical models, as the percentage of total precipitation over the aquifer area, and as the baseflow from stream interacting with the aquifers (e.g., Q_{98}, Rodríguez-Martínez et al., 2003). Different studies through Puerto Rico developed recharge estimates based on these methods. Piug and Rodríquez (1993) have estimated an aquifer recharge of 8 to 12 percent of the total precipitation in the Caguas-Juncos Valley. They performed both the water budget balance and the recharge calculation using the total precipitation for the Caguas-Juncos Valley. The results were compared at two subareas (Gurabo-Juncos and Caguas-Juncos) showed that the recharge estimates in one of the subareas (Gurabo-Juncos) were similar on both recharge methods. For the Caguas-Juncos the aquifer recharge estimated using the water balance method resulted to be approximately 50 percent more than using the other method (aquifer recharge obtained from the total precipitation) for the Caguas-Juncos. A similar method was used at the Salinas to Patillas area were the aquifer recharge was estimated as 5 to 12 percent of the total precipitation (Quiñones et al., 1995). In the study performed at the Humacao-Naguabo area, the aquifer recharge was estimated at 9 to 11 percent of the annual precipitation (Graves, 1989). This method assumes that the aquifer recharge is influenced by the rainfall. Nevertheless, aquifer source may come from streams infiltration, water running off the bedrock hills and excess irrigation (Heisel and González, 1979).

2.6. Water Quality

Another consideration that must to be included in the groundwater development analysis is quality assessment. Groundwater has generally been thought as having better quality than surface water because of its ability to filter out microbiological pollutants (Uhl et al., 2009). Nevertheless, groundwater systems may be impacted by general physical and chemical pollutants and water quality assessment must also consider. Physical-chemical water-quality characteristics include: temperature, color and suspended solids, total dissolve solids (TDS), dissolved oxygen, specific conductivity, salinity, and common ions. Common chemical contaminants in groundwater may come from mineral deposits and/or industrial facilities sources (Uhl et al., 2009).

2.7. Groundwater Resources Assessment

In the past years there has been an increase in the development of modeling and analysis techniques for groundwater resources due to the excessive use and exploitation of water resources (Kumar, 2012). This situation leads to look for methodologies and methods to analyze the groundwater resources not only as an isolated water resource but also combined with the other hydrologic cycle components (Refsgaard et al., 2009) and considering also the water quality.

Common tools used to evaluate a groundwater system include numerical and analytical models. Numerical models integrate the complexity of equations involved in the analysis (Wang et al., 2008b). Modeling results must however be interpreted within a context of uncertainty due to lack of data, and the understanding of hydraulic dynamics of an aquifer. Numerical modeling requires advance knowledge, expert input and results in time-consuming efforts with high complexity. Analytical models simplify the system but may introduce error caused by frequent oversimplifying assumptions (Bear et al, 1992).

Both analytical and numerical solutions involve the development of a conceptual model which simplifies the real system using the necessary assumptions (geometry, porous medium and other) in order to assembling a mathematical model which provides solutions or predictions of the system behavior. Analytical models are characterized for being inexpensive, providing a rapid solution and offering a groundwater analysis solution for those cases where there is not a lot of data available (Bear et al., 1992). They are, however, limited in extent. Numerical models are useful for large-scale where there is enough data or for solving complex system characteristics. One of the most common numerical models for groundwater management and planning is Visual MODFLOW ® (Harbaugh, 2005)

MODFLOW® is one of the most common modeling interfaces used. It provides a three dimensional representation of groundwater flow and pollutant transport (Harbaugh, 2005). MODFLOW ® permits to simulate systems which contain stream, river, and wells and involves parameters such as transpiration, recharge or precipitation. Some of the uses for the MODFLOW ® numerical model are water budget analysis, aquifer response time estimating, well production analysis (Walton, 1962).

Many of the groundwater models do not provide the function of optimizing the groundwater resources because of the lack of constraints and objectives definitions. Thus, the development of MODMAN tool serve as an alternative for integrating both, the groundwater modeling and management (Greenwald, 1998). The process works by assembling first the MODFLOW ® model and then after defining the constraints and objectives MODMAN ® provide the optimum problem solution.

3. Methodology

The objectives of the study were attained through a series of structured tasks. These tasks looked for developing tools and methods for analyzing groundwater resources and their integrating with an existing infrastructure. The tools and methods were applied to develop groundwater resources of hydrogeological system at the University of Puerto Rico Mayagüez Campus (UPRM) as a validation site. The objective for the validation site was to determine the feasibility of developing groundwater resources to supply the institutional water use at UPRM and integrating any development for the existing infrastructure. The tasks involved, included:

- Data collection
  - Site description and characterization
  - System characterization
  - Well production
  - Water quality, system cost and supply system
- Data Evaluation and Analysis
  - Site description
  - Aquifer characterization
  - Water extraction design
  - Constraint identification
- Data Management using GIS
  - Development of a method-based model in GIS to use tools for cost-effective groundwater resource planning, development, and management
- Site validation analysis
  - Integration of groundwater system parameters for the area of study with existing infrastructure and well field design within system constraints

The following section describes the activities associated with these tasks.

3.1. Data Collection

Proper development and management of groundwater resources requires collection of site-specific data and information including: site description (location, topography, land use), hydrogeology and soils, groundwater and well hydraulics; hydrologic components; water use; and water supply systems, water quality and system cost. The methods applied to obtain the data and information are described below. These methods were applied to obtain data and information for the UPRM validation site (Figure 5), which will be discussed at the validation site section (chapter 4).

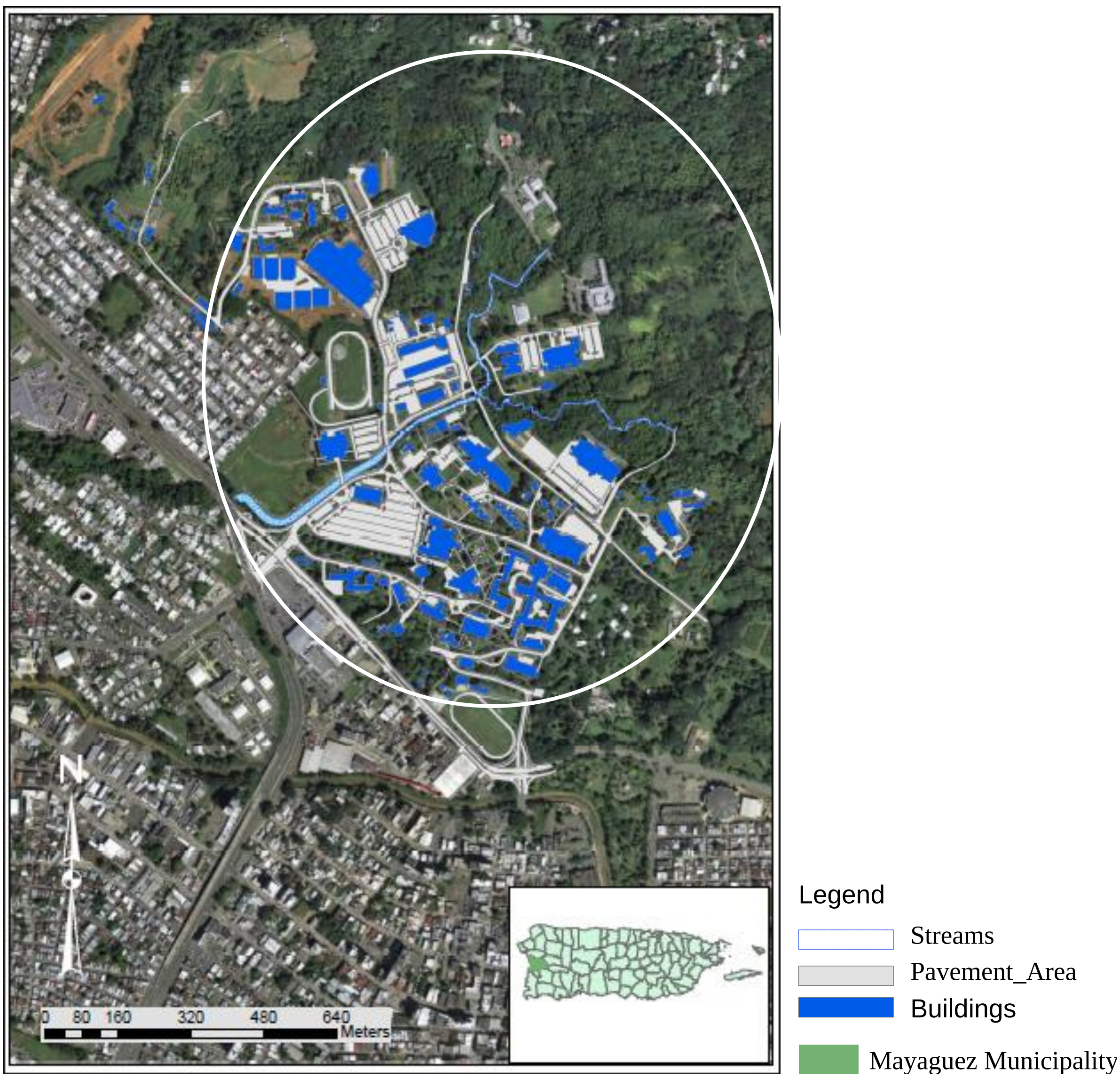


Figure 5: Location of the validation site project in Mayagüez, Puerto Rico (Flores, 2010; PRBP,2012)

3.1.1. Site Description

The site location, extent, and physical characteristics may be obtained from digital maps, satellite data, and site specific reports and maps. Digital maps may include Digital Elevation Model maps (DEM), Digital Raster Graphics (DRGs), Digital Line Graphs (DLG's), and Digital Orthophoto Quadrangles (DOQ's) which provide ground elevation data useful in the site description (USGS, 2011). There are different types of map depending of the accuracy, reference system, map spacing and area of coverage (Jacobsen, 2011). Additional information such as land use and aerial photos are used in the site description to determine the use of the surface area (urban, industrial, agriculture and rural (Anderson et al., 2001).

3.1.2. System Characterization

Characterization of the groundwater system requires knowledge on the system's hydrogeology, soils, aquifer characteristics and hydrologic budget. Development of the groundwater resources requires knowledge and quantification of the well's hydraulic performance.

3.1.2.1. Hydrogeology and Soils

Geologic, soil and hydrogeologic information is required to define the extent and determine the characteristics of the groundwater system. The geologic information is used to delineate the extent and determine the physical characteristics (make up), stratigraphy, and structure of the hydrogeologic unit(s). Geologic information may be obtained from government agencies (e.g., state geologic offices, U.S. Geological Survey (USGS), private field studies, technical reports and/or by conducting field drilling and boring investigations at the project site.

The hydrogeologic characteristics and conditions integrate flow and hydraulic elements within the geologic framework of the system, and incorporate the geologic characteristics with hydraulic heads (water levels), gradients, hydraulic properties of the aquifer boundaries, recharge, and hydraulic components. Hydrogeologic data are obtained from site-specific studies and/or reports published by the government/private offices.

Hydrologic information, including precipitation, evaporation and transpiration rates, is necessary to perform hydrologic balance and to estimate recharge rates toward the groundwater system (Manghi et al., 2009). Precipitation and evaporation rates can be obtained from government record, site-specific reports, general estimation method, and/or on-site weather measurements.

The soil type and terrain description are useful for performing hydrological and hydraulic analysis, as well as for other aspects involved in the decision-making. Soil type and terrain data may be obtained from soil surveys (USDA, 2009), area-specific report and studies from government and private offices, and boring studies at or near the site. Digital soils maps may be obtained from GIS database (PRPB, 2012)

3.1.2.2. Groundwater and Aquifer Characteristics

Aquifer hydraulic properties can be obtained from: area-specific aquifer studies reported by the state, federal (e.g., U.S. Geological Survey, Environmental Protection Agency), or private entities and literature estimates based of geological interpretations. They can also be estimated from permeability measurements of core samples, and from hydraulic testing at the field site. When possible, field-scale hydraulic testing is recommended because it integrates the hydraulic variability of the site. Aquifer tests are commonly used to determine hydraulic parameters, such as transmissivity and storage coefficients.

3.1.3. Groundwater and Well Hydraulics

Well design and assessment requires knowledge on system (aquifer) properties and performance of wells in the area. A complete survey if the area should be done to determine the properties of wells at or near the area. A well survey may provide information of well location, design, production, and performance. This information may be obtained from U. S. Geological Survey (USGS, 2012), and reports, and local and state agencies.

Well hydraulic properties and production may be accessed through a specific capacity or step-drawdown test. This test will provide information regarding the relationship between groundwater yields and drawdown in the well (Mace, 2000) and the well efficiency. The test consists in pumping a well at different pumping rates while the water levels and drawdown are measured at the pumping well (Mace, 2000). These measurements are applied to estimate the specific capacity, well and, aquifer losses coefficient and well efficiency. Specific capacity data may also be obtained from local and state water-permitting offices.

3.1.4. Design of Extraction Wells

The design of extraction wells for the groundwater development depend**s** on the hydrogeology of the site, and results from the specific capacity tests. For the validation site, well hydraulics for all proposed wells in the area is assumed to be similar to the tested well. The depth of the well, screen interval, and pump location depend on the geologic stratigraphy of the area. The diameter of the well will depend on the extraction rates (Driscoll, 1986). Extraction rates and pump capacity are estimated from specific capacity data, which is defined as the extraction rate that maximize discharge, but minimizing drawdown. Drawdown is constraint to those representing: water levels at mean sea level, levels at the bottom of a confining or semi-confining unit, and/or levels at which the ratio of drawdown to saturated thickness is less than a given percent (e.g., 50 percent), that will be determined in the study.

The number of wells required is estimated from the estimation of total water use and the extraction capacity per well. The extraction capacity is estimated from specific capacity data, corrected for inter-well effects. The location of the wells is maximize proximity to water distribution lines or target structure (minimize pipe distance), and minimize total drawdown caused by inter-well effects.

3.1.5. Water Use

Development of groundwater resources requires specific knowledge of the water use to quantify the amount of water needed for extraction and determine how much can be provided by the groundwater system. Water use data can be supplied by: appropriate institution, municipality, county and state offices; rural community and/or agricultural extension office; and industrial sector. If not available, the water use can be estimated according to the type of use, number of users, and amount consumed per user (PRASA, 1983).

3.1.6. Water Supply Network

The existing water supply network must be defined to select the adequate location for the wells that would serve as intake and evaluate the addition of alternate water supply network. The water supply network data and information (location, pipe size, valves, connections and others) can be generally obtained from planning and development, infrastructure, engineering, and water offices at the institutions, industrial complexes, municipalities, and state government. In general, that information is acquired from the office in charge and responsible of managing the drinking water system.

3.1.7. Water Quality

Water quality data are necessary to determine the quality of the water and required treatments. Coastal water quality data is necessary to assess and monitor potential effect of pumping on the salt-water interface. Water quality data and information in aquifers can be obtained from government reports and databases (e.g., USGS, EPA, and Environmental Quality Board). It can also be obtained through sampling activities at the site of interest. If the water is to be used for drinking purposes, sampling must be done for all drinking water quality standards. Water quality parameters such as specific conductance, total dissolve solids, pH, and temperature should be measured during testing and well production periods to monitor any major changes in the water chemistry of the site.

3.1.8. System Cost

The capital and operational cost of using groundwater for water supply can be estimated from well installation and pump cost, connection cost, energy cost (pumping), treatment and maintenance costs obtained from well system previously performed. It can be also utilized standard costs and estimations from wells installer companies.

3.2. Data and Evaluation Analyses

Once collected, data are analyzed to assess the factors and variables that must be incorporated on the GIS tool. Site description information is georeferenced and used to delineate characteristics of the study area. Aquifer characterization and well performance tests are analyzed to determine hydraulic properties of the system and well production characteristics. This section discusses the analysis of data that are necessary to have all evaluation factors that will be incorporated in GIS.

3.2.1. Site Description

Site description information, including aerial photos, satellite data, DEMs, DRGs, and DQQs is georeferenced and used to describe the spatial characteristics of the site. Aerial photos are applied to locate the area of study and add information that is not available from other sources (e.g., GIS shapefile, DEMs). Land use information and maps are used to define land use of area (urban, industrial, agriculture, rural). Topography data are used for hydrological and hydraulic analysis. It includes watershed delineation, evapotranspiration estimations, runoff calculations, and soil characteristics of the area. These data also provides information for determining runoff (roughness coefficient), rainfall interception (Leaf Area Index) and evapotranspiration calculations (Root Depth and Crop Coefficient) (Giovanni, 2007). The type of information that is necessary to acquire depends of the scope of the project and the methods that would be utilized for the analysis.

3.2.2. Aquifer Characterization

Proper assessment of the groundwater system requires knowledge of the hydraulic properties of the system (e.g., thickness, transmissivity, storage coefficient, specific yield). Some information can be obtained from government or private reports, but there are often generalized estimation of the properties. If groundwater resources developments is prepared at a site, proper testing should be conducted at that site to maximize objective functions (e.g., production, reduced drawdown, cost). Aquifer tests are commonly used to determine hydraulic parameters such as: transmissivity and storage coefficients of aquifers (Sakr, 2001). The aquifer test consists of pumping a well, specific discharge rates (Q), while monitoring water level overtime. Water levels are measured using a water level meter (see Appendix A) for water level measurement and determination or recorded in data logger, and drawdown ($s= h_o-h_{(t)}$) is estimated from these data.

The temporal drawdown distribution (s vs. t) is used to determine the type and hydraulic properties of the aquifers. The data may be analyzed using the *Type Curve* or linearized methods. If unknown, the type of aquifer can be determined by comparing the temporal drawdown curve with *Type Curves* of different aquifers types (see Figure 1). If the measured drawdown curve compares well with the *Type Curve* for confined aquifer, the system is treated as confined; if it compares well with any other curves for the semi-confined system, the system is treated as leaky; otherwise is treated as unconfined. Once the type of aquifer is selected/known, the pertinent method is applied to estimate the hydraulic properties of the groundwater system. The linearized method applies equation 3 to estimate properties of groundwater. For the matching method, types curve and drawdown data are overlain and matching parameters corresponding to equations 1 and 2 are obtained. Transmissivity and storage coefficient are estimated from these equations. This work applied the linearized method of analysis

3.2.3. Well Performance

Well production is estimated from specific capacity data. Theoretical specific capacity data, which is associated with aquifer losses in equation 3, can be estimated from equation:

$$\frac{Q}{s} = \frac{4\pi T}{2.3\log\frac{2.25Tt}{sr^2}} \qquad (17)$$

if the hydraulic properties are known. These theoretical estimates do not take into account well losses and the real production of the well is not known. Specific capacity estimates from measured drawdown and discharge integrate losses from the aquifer (as estimated from equation 17) and from well losess. Well losses and efficiency can be estimated from step-drawdown data (section 2.4.).

The analysis is performed by plotting SC at the end of each discharge period vs. discharge and applying equation 9 and 10 to determine well performance and efficiency

3.2.4. Water Use

Water use in the study area is analyzed by assuming a particular use rate for given uses (domestic, and the number of users). It can also be estimated from previous water supply data (meter data if available), or water billing data. This particular study used billing statements because there is an existing water supply (actual use). The billing stations for a particular site, they can be totalized in specific areas to assess if water can be supplied by the groundwater system.

3.2.5. Groundwater Recharge Estimates

Aquifer recharge was estimated using several methods: water-budget method and percentage of annual precipitation. Estimates using the water budget-method (equation 11) were obtained from precipitation, evapotranspiration and runoff estimated and/or collected using data for the selected two periods from October 1, 2000 to September 30, 2001 and October 1, 2001 to September 30, 2002 (see Appendix A). The precipitation was estimated utilizing a rainfall station data located at Mayagüez (Mayagüez City station, No. 666073) (Winter, 2009) which provided daily data of precipitation as well as the mean temperature data. For those missing values, it was utilized average values of precipitation and temperature using 30 years of precipitation and temperature database (The Southeast Regional Climate Center, 2012).

The evapotranspiration (actual evapotranspiration) was estimated using the relationship described in the equation 12 (Harmsen et al., 2002). The runoff was estimated using the soil conservation service (SCS) method that integrates the soil and land use information (Yu, 1998), and the total precipitation over the study area (equation 15 and 17). Hence, a daily water budget calculation was estimated.

As discussed in the section 2, the aquifer recharge was also estimated using the percentage of the total precipitation over the study area and it is described later on the chapter 5.

3.2.6. Identification of System Constraints

The tools and methods developed in this study integrated water use with the physical, hydrological, and groundwater hydraulic characteristics and constraints of the hydrogeological and water-supply infrastructure systems. It is necessary to determine which constraints limit the groundwater development. Constraints are quantified into criteria parameters, and may include: water extraction per well (based on specific capacity (SC)), location of wells, drawdown at wells, total extraction (depending of recharge estimates), water quality changes, and cost. Extractions per well in this study (Q) are constrained by drawdown and their associated potentiometric water levels. Drawdown can be constrained to those representing: water levels at mean sea level; levels at the bottom of a confining or semi-confining unit; and/or levels at which the ratio of drawdown to saturated thickness is less than a given percent (e.g., 50 percent). Locations of wells are limited to open areas and by distance to water line connection or water supply target structure (e.g., a particular building). The total amount of groundwater for extraction is limited by the amount of estimated recharge and depends on the water use required.

3.3. Data Management and Assessment Using GIS

All the information and data collected were integrated into a hydrogeologic-water use model and evaluated using GIS technologies. The model incorporated hydrogeologic aspects (geology, soil, hydraulic properties, potentiometric water level), well hydraulic properties, water network, and land use data into the ArcMap database, and is used to optimize and visualize the spatial distribution of potential groundwater intakes points and water supply connections. Using GIS, the data were segregated into characteristic parameters of depth (water level, hydrogeologic cross sections and vertical drawdown) and distances (from water lines, wells, target structures and radius of influence/horizontal drawdown).

Data characteristics were soverimposed and analyzed within the context of a number of base map**s** using ArcGIS 10 (ESRI, 2011). This GIS platform uses intelligent data models for representing geographical features, and provides the necessary tools to create and work with spatially-distributed data (ESRI, 2005). The proposed methodology was applied to the UPRM validation site area (shown in Figure 5). This section discusses the process performed to support making decision making tools necessary to properly manage groundwater resources in the study site.

Figure 6 summarizes the components that were considered to develop the method-based GIS model and assessment plan. The model incorporates all the data and information required for the analysis. Then it performs the groundwater and water use analysis, and determines optimal groundwater development strategies. GIS model also served as a tool to visualize the project characteristics and integrates a decision-making criterion that permits to determine the feasibility of developing the groundwater resources in the area of interest. Thus, the next chapter will present the methodology and the proposed process used for the validation site at UPRM.

3.3.1. Problem Statement

It is necessary to initially identify the area extent of the groundwater development project. It must include the justification to look for the feasibility of developing water resources which may be based on economic, politics, or environmental aspects. There are cases in which there is an existing water infrastructure but still needs an alternative for water supply as well as other cases where there is no previous groundwater supply source. In both cases it is required to establish the scope of the project to then determine the process to follow. Once the main need for proposing groundwater resources development has been established, the delineation of the extent of study area must be done in order to gather all the information necessary to analyze the system and have the decisions making tools for the water recourses development.

3.3.2. Collection and Management of the Data

This section provides a general description of the development of GIS tool for managing and analyzing the data collected in order to integrate the hydrogeologic-water use model.

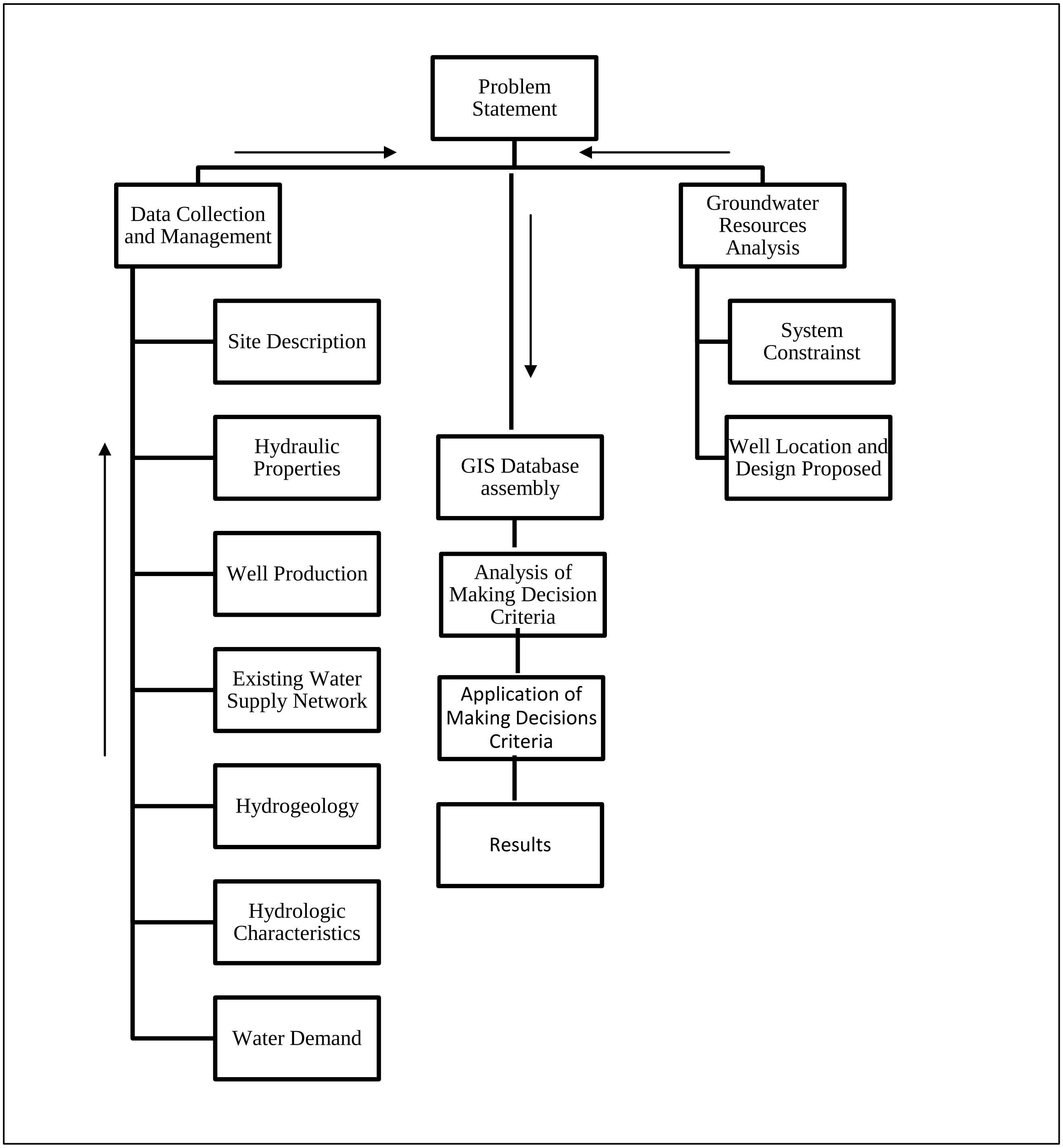


Figure 6: Flowchart describing the groundwater assessment as a water supply intake

3.3.2.1. Delineation of the Site

The delineation of the study area may be given either by shape-files containing buildings extent, roads, water bodies, infrastructure, land elevation and land use or by aerial photos and analogous maps which can be input to the model. There are cases where more than one source is used, requiring geo-referencing of the input data according to the desired coordinates system. The coordinate system is initially defined when assembling of the GIS model is done to allow visualization of the spatial information and comparison with different features of the study area. The appropriate coordinate system depends of the original format of the input data, but GIS provides different alternative tools to define an existing coordinate system or convert from a coordinate system into another one. These tools include: *ArcToolBox/Data Management Tools/Projections and Transformation* which permit either of them.

Considering the difficulty for acquiring the data and that the data comes from different sources, it is common to have information coming from existing shapefiles or the creation of shapefiles to input the data.

3.3.2.2. System Characterization

In general, for groundwater resources the characterization involves mainly the description of the geology, hydrogeology, aquifer and wells hydraulic as well as other hydrological aspects (precipitation, evapotraspiration, etc.) of the desired site. In general, this kind of information may be input to the ArcMap using the following methods:

- Using existing shapefiles containing information related to the hydrogeology, geology, aquifer extent and the needed data to describing the system.
- Using another input format such as text, images or analogous maps and converting them to the desired coverage feature class. Tools converting x and y coordinate data into layers (e.g., *Display XY Data)* serve to input well(s) coordinates or another point features, create shapefiles and digitalize analogous data (maps, images, diagrams

etc.). The *Spatial Analyst* tool provides applications for creating precipitation and evapotranspiration raster map, groundwater flow raster map and contour elevations maps.

- Adapting the existing coverage into a new one containing information such as radius of influence of the well, cover distance for building, roads or bridges. This action may be performed using different features of *ArcToolbox/Analysis Tools*, including the *Buffer, Clip, Erase* and other applications for creating new coverage features.

3.3.3. Integration System Constraints

System constraints (Sec. 3.2.6) are incorporated in the GIS model by establishing criteria for well location based on land use, closeness to water distribution lines, and total drawdown in pumping wells. Locations of wells are limited, in the case of this study, to open areas (eg. areas not occupied by building and other structures, pavement). GIS is applied to digitize those are and classify them as potential for groundwater development. Once the total minimum number of required wells is estimated, the wells are located in open areas closed to water distribution lines. Drawdown is estimated and the effect of drawdown interference by multiple wells is integrated in the GIS model. If all criteria are met, the number of wells is increased, discharge per well and drawdown decreased, and wells redistributed iteratively until the criteria are met. Criteria parameters are therefore integrated into the GIS mode and used to optimize extraction rates, number and location of wells, and system cost.

3.3.4. System Integration

Using GIS technologies, groundwater system data characteristics for the study site were integrated with well hydraulic data, water use, and the infrastructure in the study area. Well field is designed according to the water needs and system constraint criteria. Several general tasks and considerations are used for the system integration in this study. These include:

- The extent of the area of study was designated according to the scope of the project established in the problem statement and the extent of the aquifer is delineated according to the hydrogeologic data. All site description information is integrated in GIS.
- Recharge rates are estimated for the area of study.
- Aquifer and well hydraulic properties and the extraction capacity of testing wells are quantified from the aquifer and specific capacity tests. The methods are applicable if available.
- The water use is estimated from previous water billing statements for the area of study, to determine the amount of water needed from the groundwater system. The total amount to be extracted from all wells must not exceed the values estimated. The number of wells required to supply the expected water use are e, based on specific discharge and drawdown constraints.
- The locations of the wells are determined initially from data characteristics and constraints assigned in GIS (e.g., open spaces, proximity to water lines and target structures).
- Spatial and temporal drawdown are estimated for all the wells and superimposed in the groundwater system model to estimate the total drawdown in the well system resulting from multiple well interaction effects.
- The location of the well(s) are selected by minimizing the distance from well to connection point and maximizing the distance between pumping wells to reduce the effect of multiple wells on well drawdown and by maximizing groundwater extraction.
- Cost estimates using from groundwater is estimated by considering the construction and operation cost or by applying a unit cost per well
- The outcome of the integration results in the development of a method-based model and assessment plan in GIS to provide tools for cost-effective groundwater resource planning, development, use, and management. This means that groundwater extractions are optimized, drawdown minimized, and cost optimized.

4. Site Validation at UPRM

The University of Puerto Rico Mayagüez Campus (UPRM) was selected as a study site validating the groundwater resources development process using GIS model. The validation site serves to verifying if the proposed model satisfies the objectives established. In addition, it serves as an example of a real case of groundwater resources development within an existing infrastructure area.

UPRM serves an academic community of 12,474 students and 2,769 employees (Institutional Office of Research and Planning, 2012), and provides a number of community, academic and professional services to a significant number of members outside of the institution. UPRM is a land grant institution (Research and Development Center, 2012) and provide services for the development of agriculture, science and engineering. As a Sea Grant College (Research and Development Center, 2012), UPRM is also involved in scientific research, education, training, extension conservation, and practical used of coastal and marine areas.

University of Puerto Rico at Mayagüez (UPRM) requires about 72, 353, 555.076 million gallons of water per year, leading to a monthly average cost of $73,000 (PRASA, 2010) for water resources. In addition to this excessive cost, the water supply in this system is unreliable, resulting in an unacceptable number of days without water service that imposes an economic burden to the institution in operational costs and hinders its ability to provide proper services. Estimated economic losses for each day without water at UPRM are $440,000 (Vallejo, 2012).

4.1. UPRM Site Description

The UPRM is located in the Mayagüez Municipality at the western coast of Puerto Rico (Figure 5). Mayagüez County has a total population of 89,080 people (U.S. Bureau of Census, Washington 2010). The campus is bounded on the north by urban and agriculture areas on the Mayagüez Landfill, on the east by the Mayaguez Zoo and rural land, on the south by the urban and agricultures areas and on the west by urban, industrial and coastal areas the Port of Mayagüez (Figure 5). The climate of Mayagüez is characterized for having a typical dry season from January to July and wet season from August to December. The annual average temperature is about 80 ºF and the annual precipitation is 69.74 inches (NOAA, 2009) and about 80 inches in the coastal areas (Rodríguez-Martínez et al., 2003).

Mayagüez is located on a coastal valley, and consists of mild to flat terrain in the coastal deposits and alluvial valley, and with sloping ground and mountainous terrain in the eastern part (Pando et al., 2006) The topography at UPRM can be catalogued as variable having steeper and milder slopes, with elevations varying between 45 to 15 meters above mean sea level according to the contour map generated using the DEM data (USGS, 2011) and the GIS Spatial Analyst tool (Figure 7). The higher elevations are located at the northern and eastern zones of the site and the lower elevation at the southern and western.

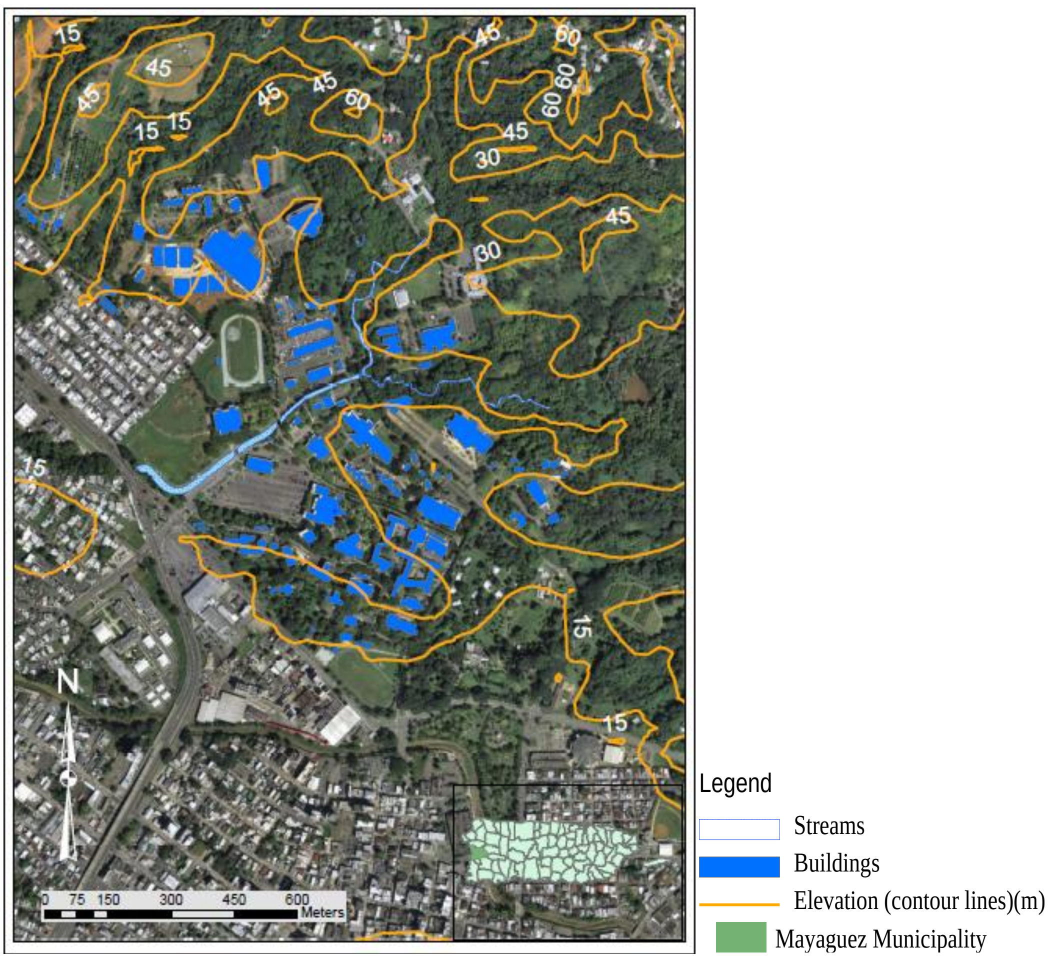


Figure 7: Topography of the validation site at UPRM (PRBP, 2012)

4.2. System Characteristics

The geology of the Mayagüez area lies between the contacts of the Sierra Bermeja complex and a volcanic complex (Pando et al., 2006; Moya and McCann, 1992). The Sierra Bermeja Complex is composed mainly by volcanic and metamorphic rocks. The volcanic complex is a folded sequence of sedimentary and volcanic rocks that overlay the Sierra Bermeja Complex. The areas near to shoreline are to a large extent sand beach deposits characteristic of coastal environments. These sands are composed mainly as moderately to well sorted, quartz sands. Near the rivers the soils are alluvial deposits described as poorly to moderately sorted. UPRM site lies on two geologic units (Figure 8) Yauco Formation and Alluvium (Pando et al., 2006). The Yauco Formation is characterized by having calcareous volcanoclastic sandstone, siltstone, clay stone, limestone, breccias and conglomerate. The geologic unit alluvium is then characterized for sand, silt and gravels which include rock falls and landslide deposits (Pando et al., 2006).

Borehole and geophysical assessment data at the UPRM (Abrams, 2010) provide geologic information of the study area. Drillers logs of a pumping well CP and on observation well CO at the UPRM (Figure 9) indicate that the wells are drilled through clay media into weathered rock (Figure 9). Geophysical and geologic interpretation classifies the system as transitional saphatite weathered rock overlain by latent (Abrams, 2010). This information indicates that the UPRM wells tap weathered rock under confining or semi-confining conditions.

According to the soils map obtained from the GIS database of the Puerto Rico Planning Board (PRPB) (Puerto Rico Planning Board, 2011), the site is characterized for having mostly clay soils and leveled land frequently flooded (Figure 10). Clay soils included Bajura clay, Daguey clay, and Consumo clay. Bajura clay is described as poorly drained soils while Daguey and Consumo clays are characterized for been well drained soils. The information provided from this database can be used for hydrological purpose where soil characteristics are important and other aspects in the making decisions process.

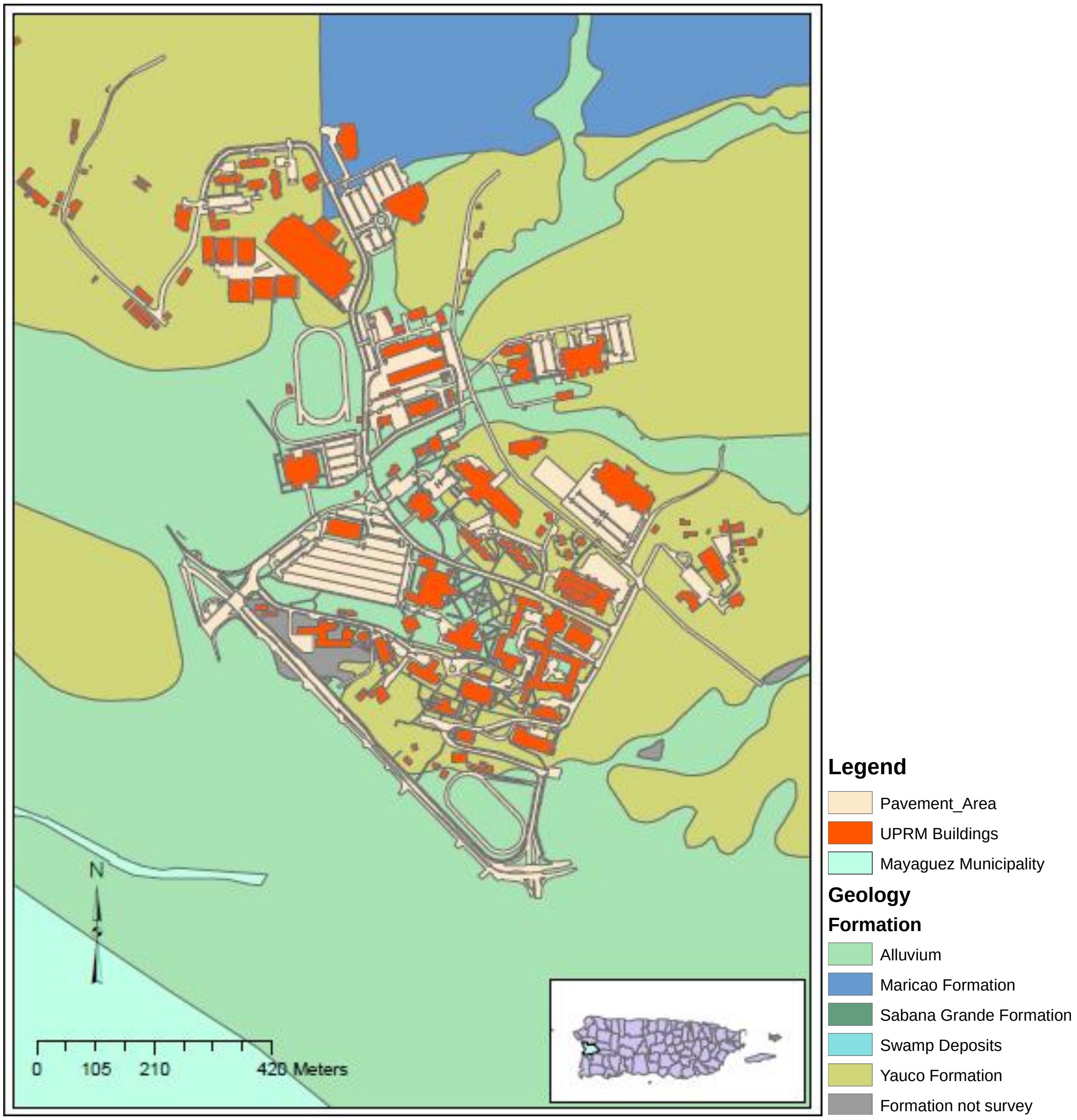


Figure 8: Geologic map of the UPRM site (Flores, 2010; PRPB, 2012)

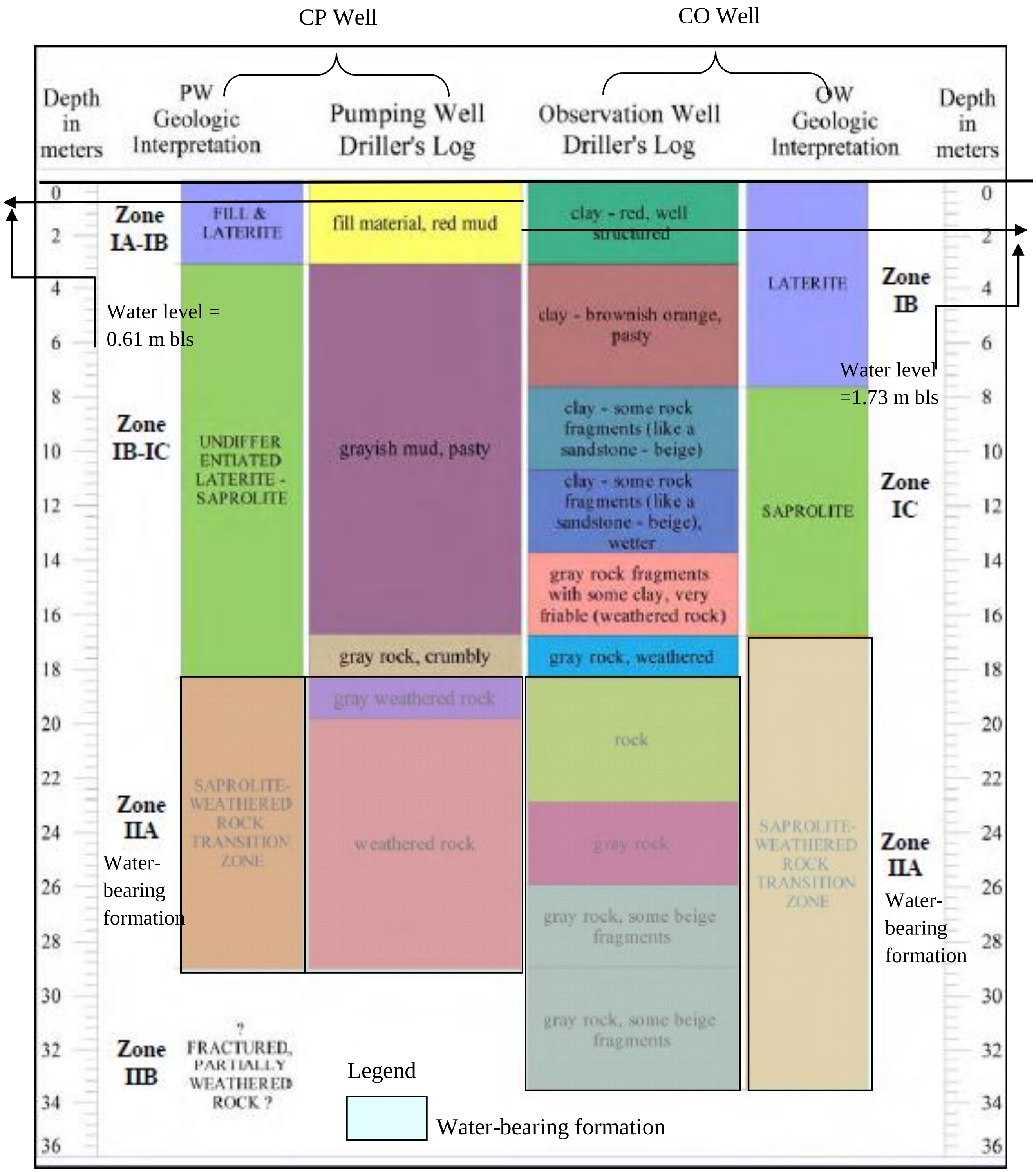


Figure 9: Boreholes corresponding to the CP and CO wells located at the UPRM site (Abrams, 2010)

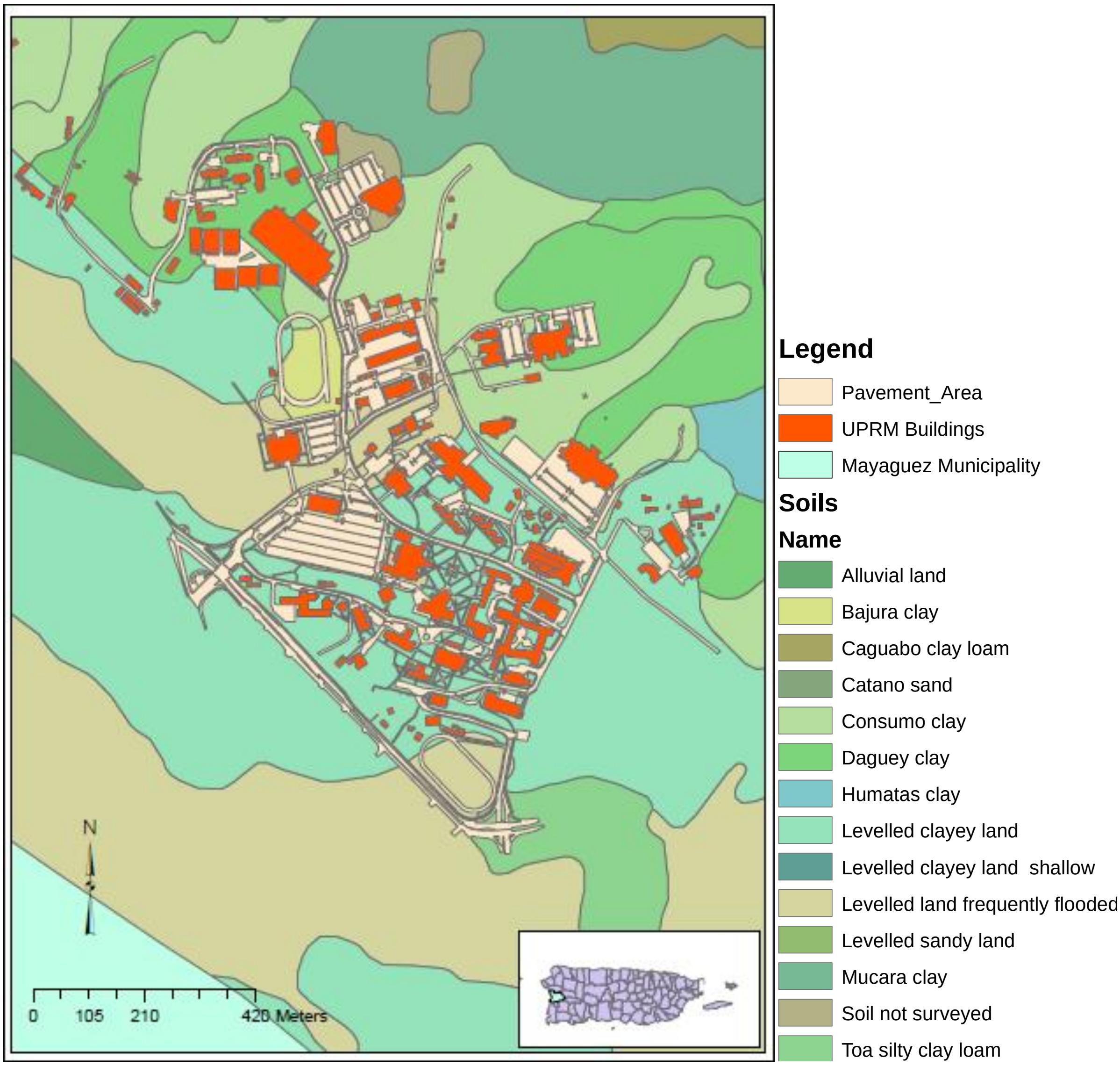


Figure 10: Soil map corresponding to the UPRM site (Flores, 2010; PRBP, 2012)

The hydrogeologic characteristics at UPRM were obtained from published hydrogeologic reports and from GIS database from the PRPB (Puerto Rico Planning Board, 2011), and the hydrogeological reports by Pando et al. (2006) and Rodríguez-Martínez et al. (2003). Rodriguez et al. (2003) divided the area in five hydrogeologic terrains according the hydrogeologic and groundwater characteristics: MayHT1, MayHT2, MayHT3, MayHT4 and MayHT5 (Figure 11). UPRM is situated at the MayHT1 and MayHT3 hydrogeologic terrains. The MayHT1 terrain is restricted to the lowlands, which include coastal areas and alluvial terraces along rivers and creeks. It consists of an upper and a lower zone. The upper zone is composed mostly of Quarternary alluvium. The alluvium is predominantly fine grained and is composed largerly of silt and clay with minor amounts of sand. The Quaternary-age alluvial terraces along the rivers and creeks in the mountainous interior generally are coarser grained than those in the coastal areas. Groundwater in the upper zone occurs under water-table conditions. Groundwater level data indicate that depth to the water table is generally less than 10 ft below land surface (Rodríguez-Martínez et al., 2003). Flow in this zone is predominately with probable local flow component with stream interactions.

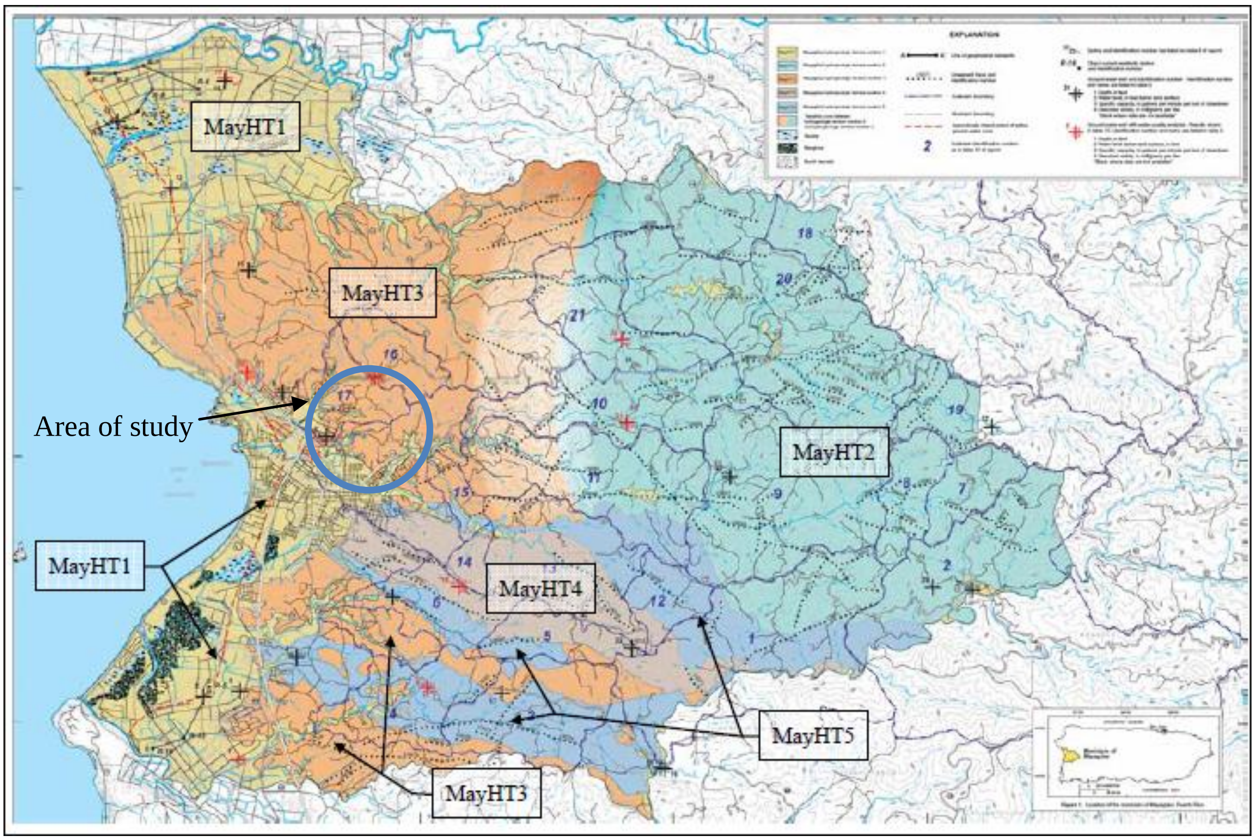


Figure 11: Hydrogeologic Map of Mayagüez, Puerto Rico (Rodríguez Martínez et al., 2003)

The lower zone of the MayHT1 hydrogeologic terrane consists of pre-Quaternary fluvial and marine sandstones and Late Cretaceous and Early Tertiary-age volcaniclastics (sandstone, siltstone, claystone, breccias, and manconglomerate) and limestones (see Figure 11). The vertical and horizontal irregular characteristics of the system lithology imports heterogenous characteristics of the groundwater system in this zone. The irregular occurrence of permeable and non-permeable units account for the presence of confined or semi-confined groundwater conditions. This unit is characterized by low permeability of low productivity. Wells tapping limestone strata may view higher rates, but wells tapping volcaniclastic units of the lower zone have specific capacities that range between 1 and 2 gallons per minute per foot of drawdown (Rodríguez-Martínez et al., 2003). Water levels near and above level surface reflect artesian conditions (Rodríguez-Martínez et al., 2003) with a regional flow component. Recharge in the MayHT1 is largely from precipitation, which is about from 80 inches in coastal areas (Rodríguez-Martínez et al., 2003). It was estimated that recharge in this zone can vary from 0.05 to .25 m/year (Rodríguez-Martínez et al., 2003).

The hydrogeologic terrain MayHT3 consists of volcanoclastic rocks introduced by intrusive igneous rocks. The geologic units present in the MayHT3 are the outcrop equivalent of these units in the lower zone of the MayHT1 hydrologeologic terrain (Rodríguez-Martínez et al., 2003). Similar to MayHT1, this zone is characterized by low permeability. Wells in this zone have shown specific capacities from about 1 to 2.5 gallons per minute per feet. (Rodríquez-Martínez et al., 2003). Water levels in the MayHT3 flowchart between 1.8 and 27.44 meters below land surface and the lithologic data suggest that groundwater occurs under confined conditions.

A survey of wells near the UPRM site indicates that there are several wells at the site (Figure 12). Table 2 shows general information of the well at the site. The horizontal coordinates system used is the state plane NAD 83 Puerto Rico 5200 m (Environmental Modeling Systems, 2012). The wells locations were obtained from the field survey data excepting for the (M2) which was located using Google Earth (2012).

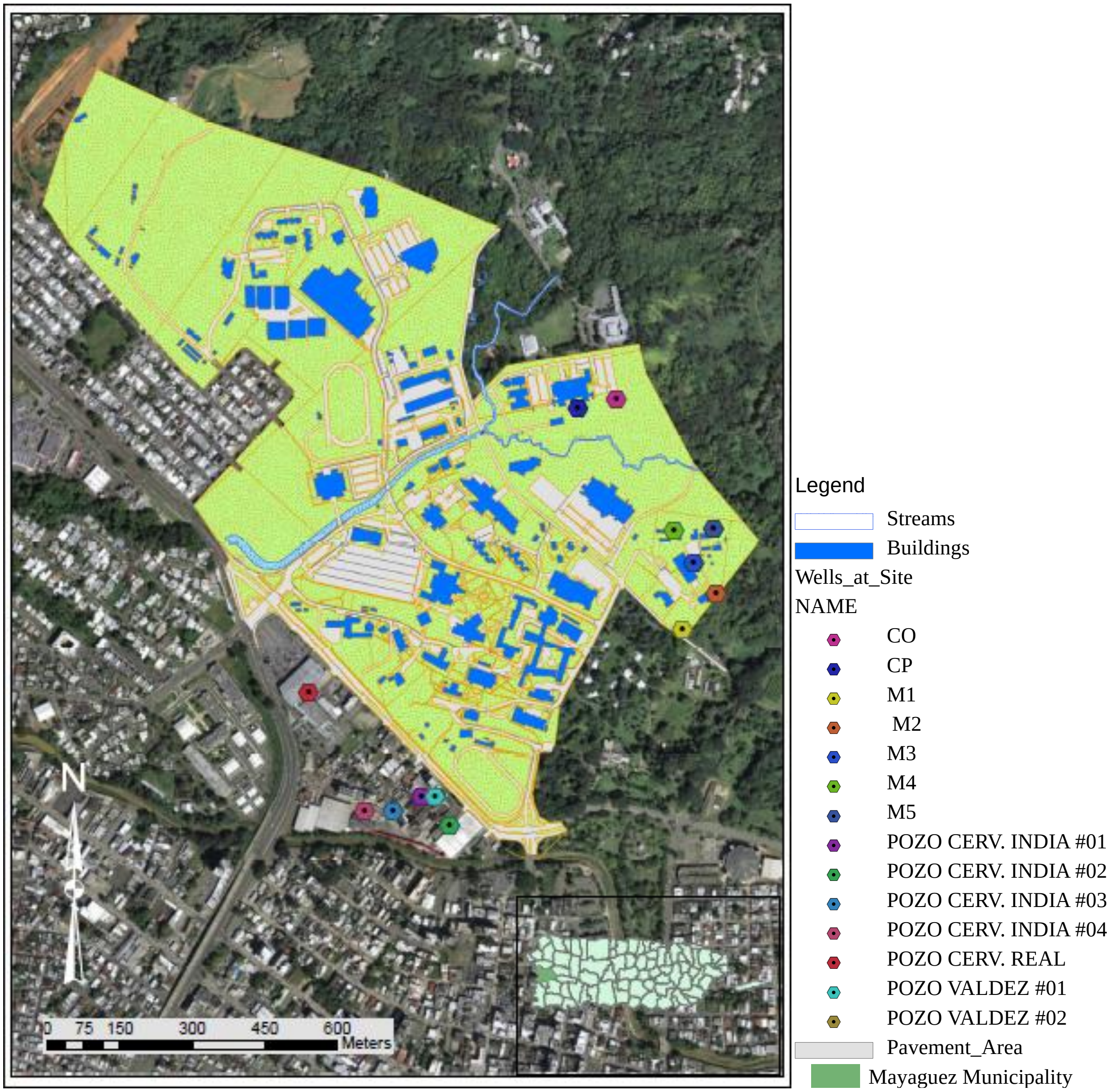


Figure 12: Wells survey location (PRPB, 2012)

Table 2: UPRM wells description

Well Name	X Coordinate (SP NAD 83)	Y Coordinate (SP NAD 83)	Ground Elevation (ft) (amsl)	Well Depth (ft)	Water Level (bls)
M1	125564	241866	19.5	35.13	22.33
M2	125635	241943	32.5	78.8	65.10
M3	125588	242004	31.8	79.57	62.57
M4	125547	242072	31.8	79.64	65.67
M5	125630	242075	33.6	88.48	70.78
CO	125349	242325	12.8	95	2.13
CP	125428	242346	14.45	105	4.99
Pozo Valdez #2	124778	242696	65	54	36
Pozo Cerv. Real	124790	241748	7	115	2
Pozo Cerv India #1	125021	241520	22	100	9
Pozo Valdez #1	125052	241516	22	105	24
Pozo Cerv. India #4	124902	241497	10	100	20
Pozo Cerv. India #3	124959	241489	15	Not available	14
Pozo Cerv. India #2	125079	241459	25	Not available	Not available

Aquifer and well hydraulic characterization in this research involved measuring water levels in wells located in the study area. These measurements were taken in 5 wells located in the UPRM Research and Development Center (UPRM-CID), identified as M1, M2, M3, M4, and M5 in Figure 12 and Table 2, and 2 wells located just south of the Civil Engineering building at UPRM. The wells near the Civil Engineering included a pumping well and an observation well and are identified as CP and CO, respectively, in Figure 12 and Table 2. The pumping well (CP) extends 29 m bls (below land surface) with a screen located between 16.7 and 29 m bls, and the observation well (CO) extends 32 m bls with a screen located between 19.8 and 32 m bls (Figure 13)

Measurements taken in the UPRM Research and Development Center (UPRM-CID) and Civil Engineering wells show water levels ranging between near land surface and 23 meters below land surface (Figure 14). Water levels do not vary significantly across the year (approximately 2 meters). Water levels near and above land surface indicate confining or semi-confining conditions.

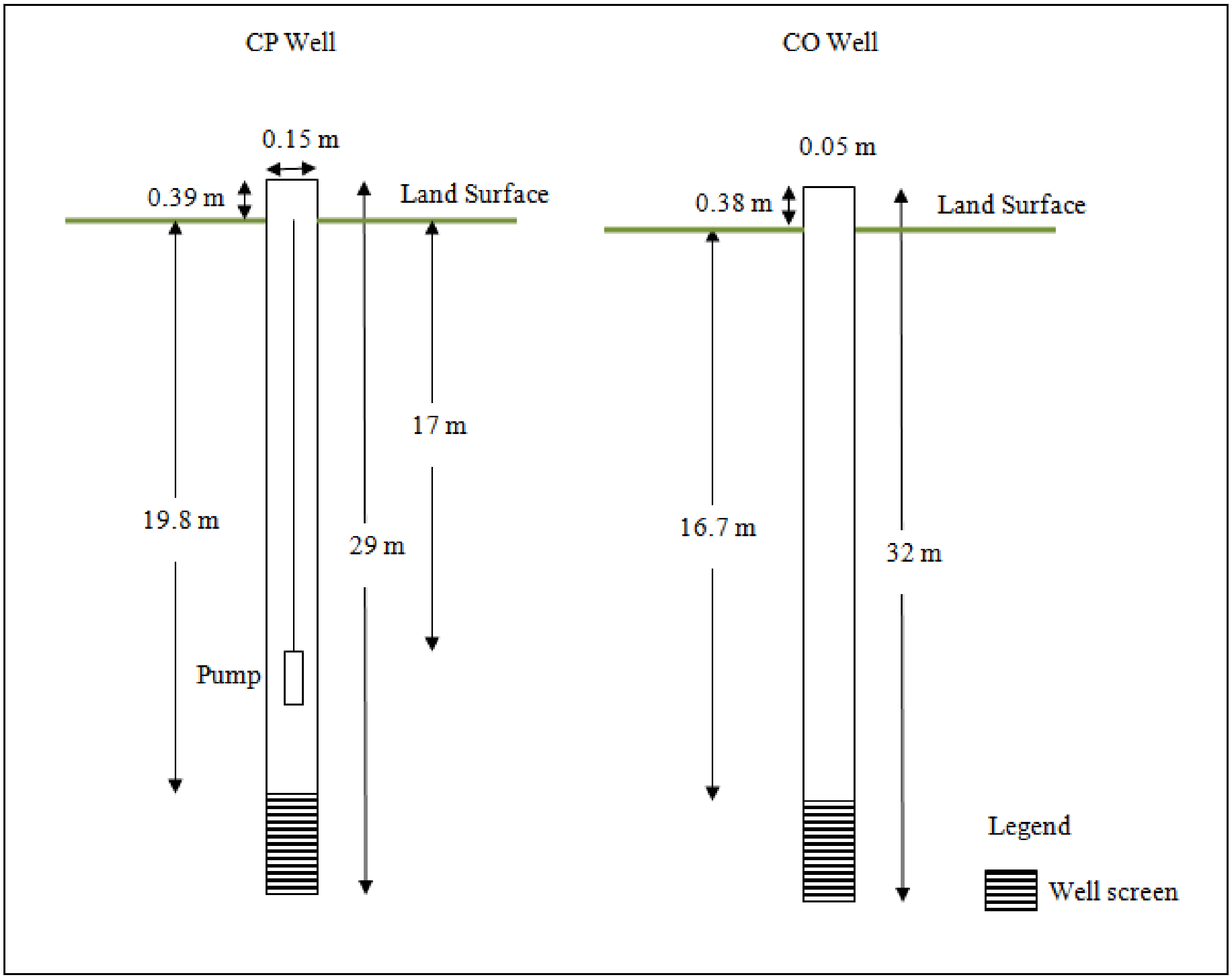


Figure 13: General description of the CP well and CO well

The hydraulic properties of the UPRM validation site system were obtained by performing aquifer tests. The tests involved pumping of the well located at the Civil Engineering and Surveying (CP), while monitoring water levels at the pumping well and several observation wells located at UPRM (Figure 12). These wells were drilled into fractured/weathered rock underlying the site (Abrams, 2010). Drawdown analyzed in space and time to determine the type of aquifer and its hydraulic properties (K, T, S, S_y) (Equations 1 and 2). These properties are applied in the Theis equation 1 to estimate drawdowns in the aquifer caused by the proposed wells.

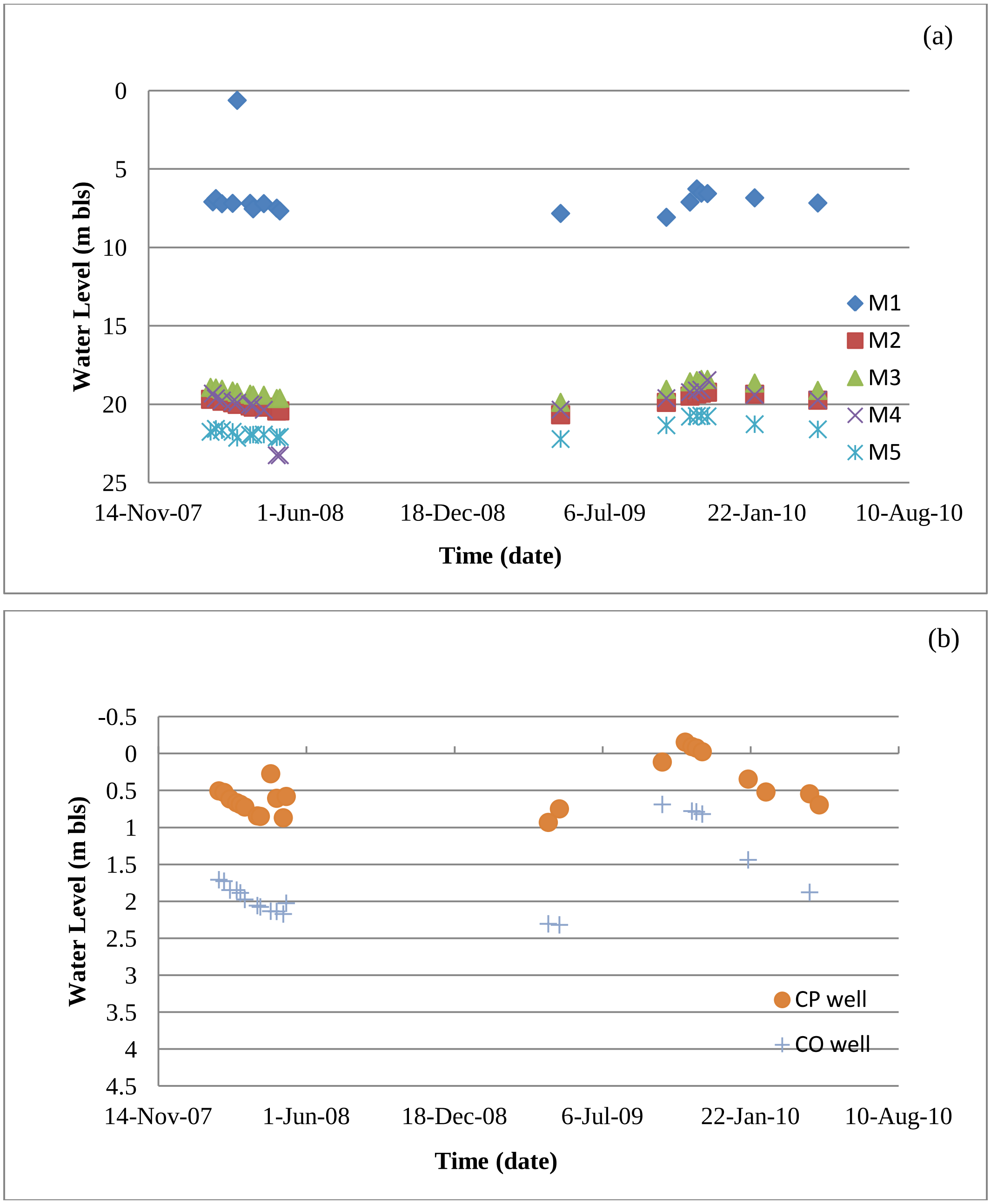


Figure 14: Water levels (bls) for the wells located at the (a) UPRM-CID and (b) Civil Engineering and Surveying Department

Three aquifer tests were performed at different pumping periods and flow rates. Table **3** shows the date, time of the testing, and the average flow rate used in the aquifer test. Flow rates were measured with a flow meter (Appendix B, Rate/total paddle-wheel flow meter) was installed in the pumping well.

Table 3: General aquifer tests description

Aquifer Test (AT)	Starting Date	Pumping Period (hrs)	Flow Rate (m^3/ day)
1	May 9 , 2009	24	446.83
2	September 25, 2009	108	370.45
3	December 9, 2010	336	311.45

Water levels were measured (Appendix C) using a portable water meter (Powers Well Sounder, model PWS100M) (Appendix B), and a Solinst Levelogger (model 3001) (Appendix B). The levelogger was installed in the observation well and it measured water levels in intervals of 15 minutes.

In addition to measuring the water levels for the wells during the aquifer test, water quality parameters were measured to assess any changes in water quality during the pumping periods. Measurements were conducted with a water quality multimeter (HydroLab Surveyor 4) and included: temperature (Temp), Specific Conductivity (SpC), Dissolve Oxygen (DO), Total Dissolve Solids (TDS), Chlorophyll (CL), Salinity and pH. The measurements were taken once per day during the aquifer test performed during the 336 hours test. The parameters were measured from a bucket, in which the water from the pumping well was collected.

Water use and distribution system data for the validation site were estimated from water bills invoiced by the Puerto Rico Aqueduct and Sewer Authority (PRASA, 2011) to the UPRM. These data were provided by the UPRM Buildings and Terrains Department of UPRM, and were estimated for different institutional complexes based on the water meters. There were seven water meters utilized for the project. Figure 15 shows the approximate location of the water meters and the buildings which receive water service from it. The water meters were named CAAM Pool, Civil and Chemical Eng., Physic, Alzamora, La Vita, Biology, Chemistry and CID. The water use data was obtained for a time period of approximately 2 years (2009 – 2011).

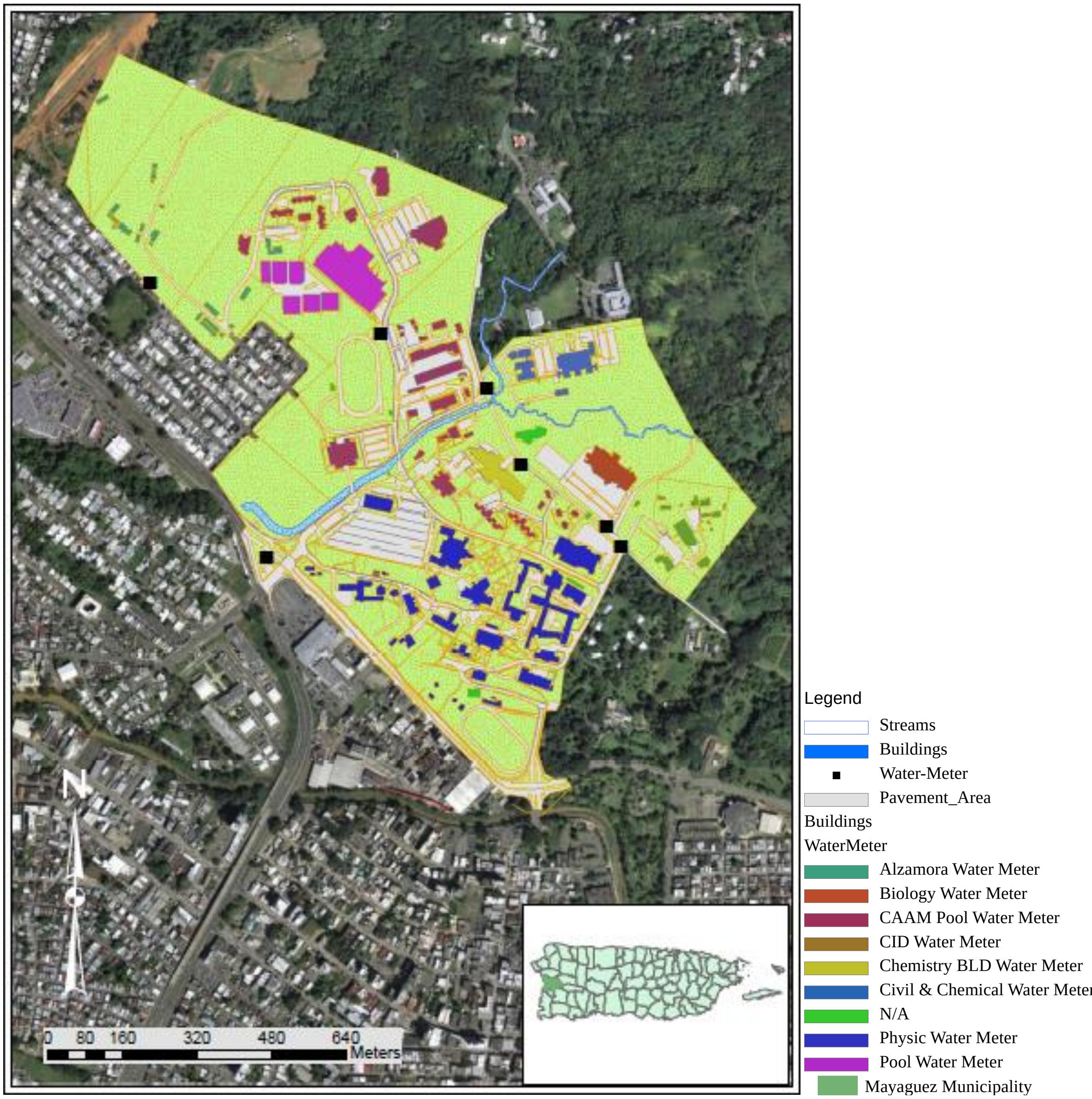
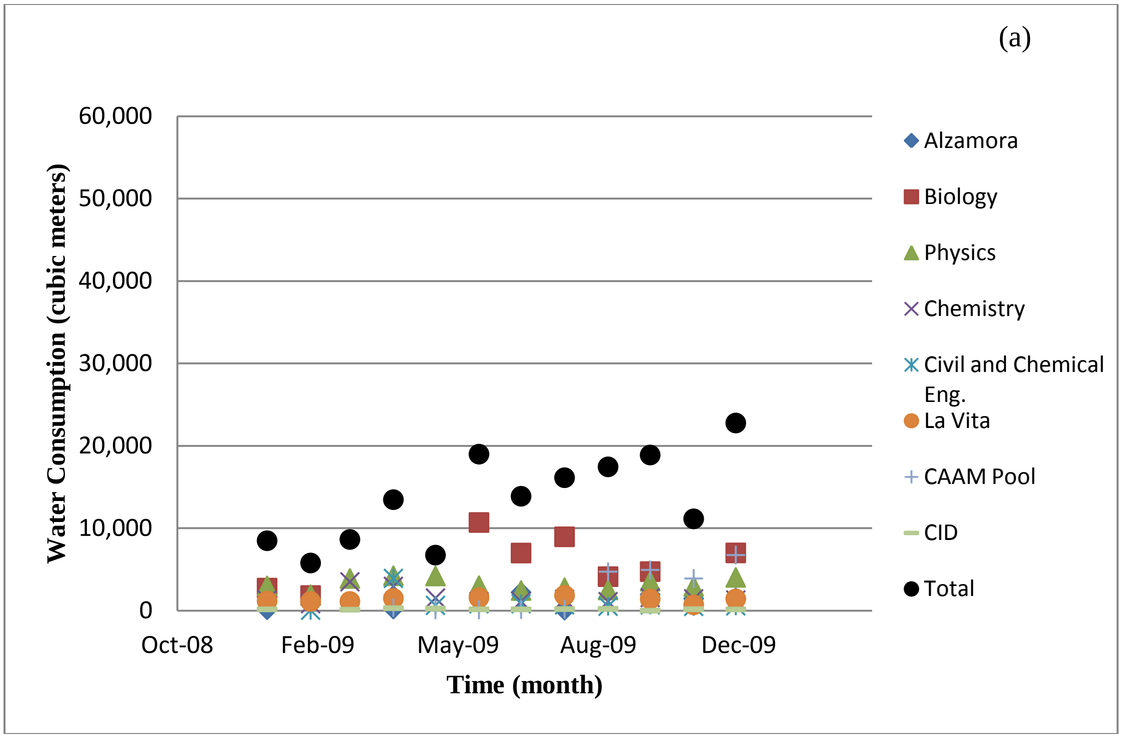


Figure 15: UPRM buildings classification according to connection to water meters



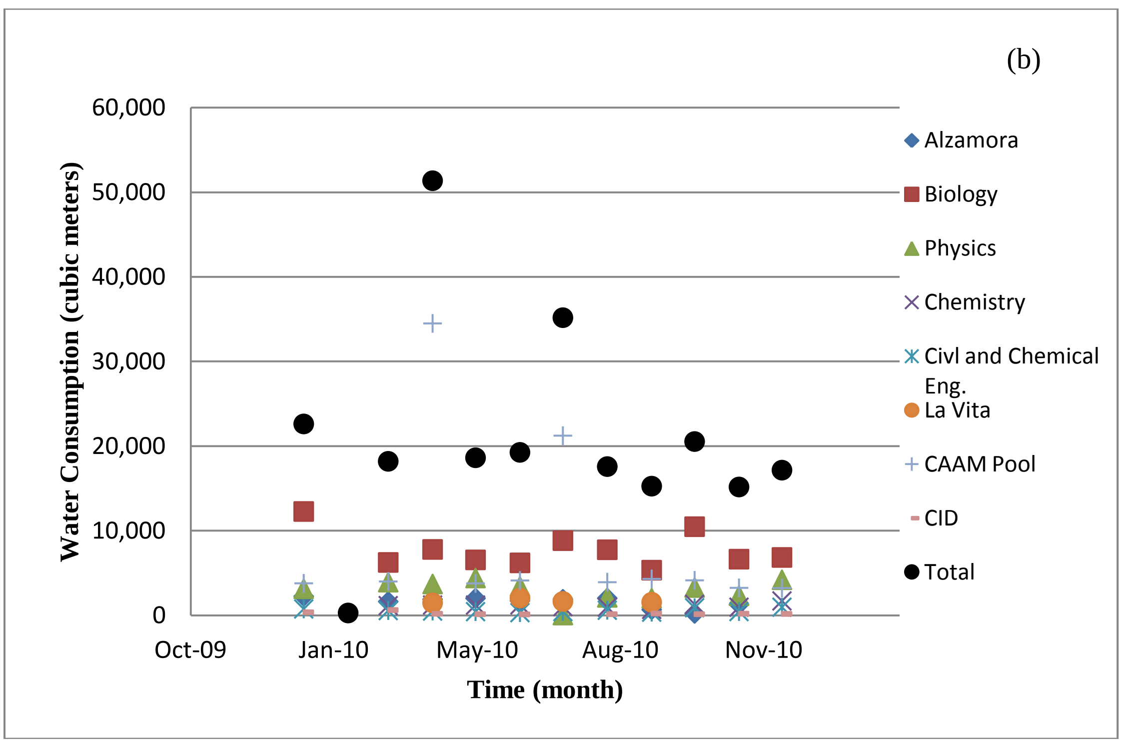


Figure 16: Water consumption of UPRM for the main water meters (a) 2009 and (b) 2010

Water consumption between January 2009 and December 2010 (Appendix D) show little variations in water consumption (Figure 16). The total average water consumption per year is around of 208,379 m^3 of water and the average monthly water consumption is 17,127 m^3 (approximately 571 cubic meters per day). It is important to note that there are missing lectures due to problems in the equipments (water meters), missing of water meters lectures, and other situations in which water consumption could not be quantified. Although not an exact measure of the water consumption, this information provided accurate estimates on water consumption.

The distribution of the water networks at the UPRM validation site were obtained from the UPRM Buildings and Terrains Department (Ortiz and Medina, 2010). UPRM data was provided in paper drawings and from interviews with the Buildings and Terrains Department's personal (Ortiz and Medina, 2010) provided the existing water distribution of UPRM. This information was incorporated using GIS to create a database of the water distribution of the validation site, digitalize the information and create the shapefile containing the water distribution layout. The hard copy of the UPRM water distribution system (Appendix E) was initially uploaded into GIS as an image and georeferenced using reference points. Two points (see Table 4) were obtained by survey measurement and acquired from Perez-Alegría (2010). Once georeferenced, a shape file was created, in which the water distribution was digitalize using the water network layout as a reference (Appendix E).

Table 4: Reference point used for georeferencing UPRM images (SP NAD83 PR)

Reference Point	East (m)	North (m)
1	124732.7632	241942.5458
2	125561.9955	242006.2259

Because the UPRM water distribution drawings did not have the complete system included, personal interviews with plumbing employers from the UPRM Building and Terrain Department were performed to complete the layout of the UPRM water distribution system (Ortiz and Medina, 2010). This was used as the most current layout of the UPRM system (Appendix E) and was assembled as the complete shapefile containing the water distribution system.

Additional information such as buildings and streets location were obtained from Flores (2010). Using all the provided information, a GIS database containing the diameters and the approximated location of the pipeline system of UPRM was created. Figure 17 shows the final Water Supply Network layout of UPRM which was issued in the GIS model. The water distribution network is used for the selection of the well(s) location.

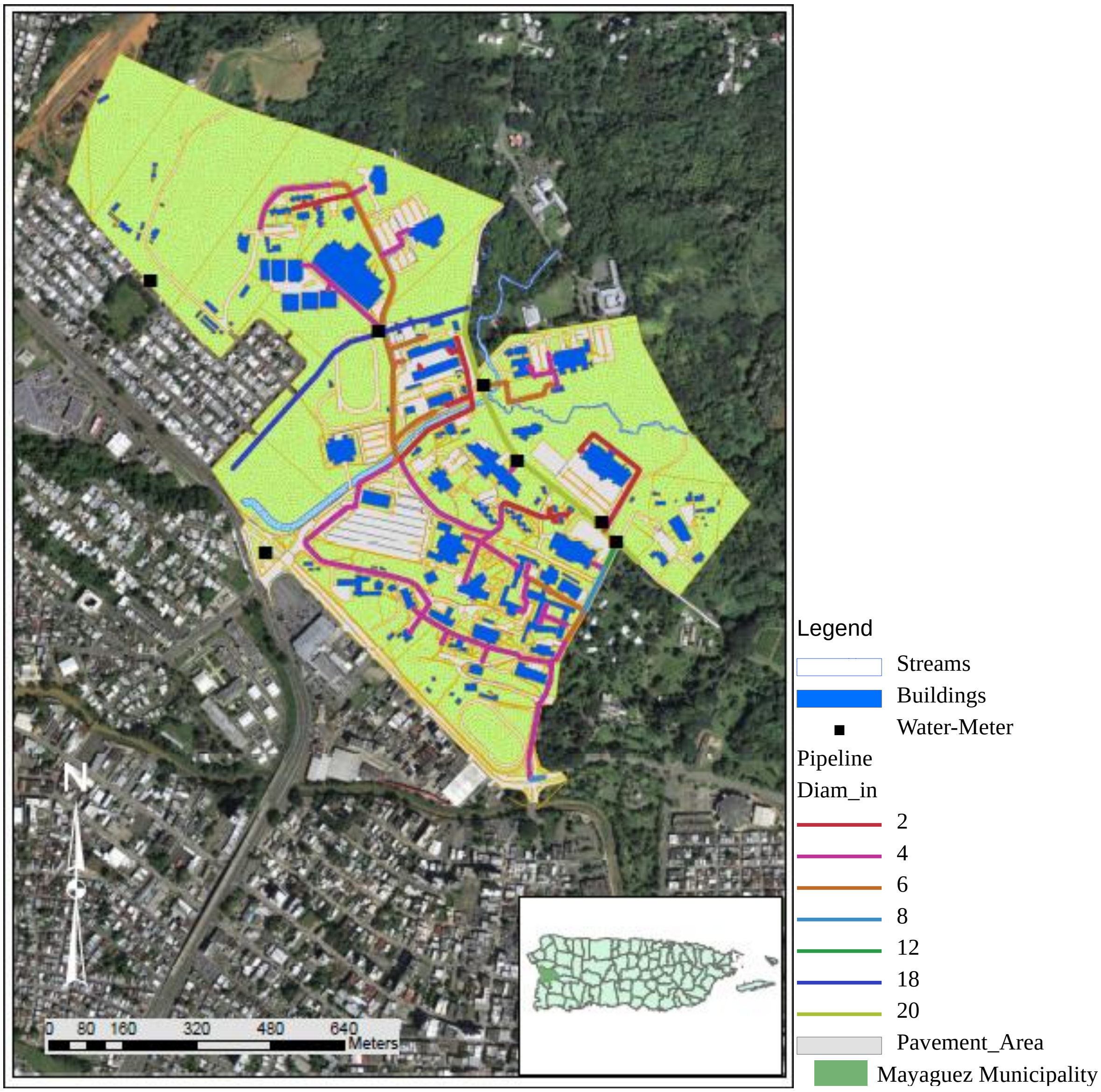


Figure 17: Final water distribution system layout of UPRM validation site (Flores, 2010; Ortiz and Medina, 2010)

Well hydraulics and performance data were obtained for the Civil Engineering Pumping Well (CP, see Figure 12) using specific capacity tests (section 2.4.1). This research conducted five step-drawdown tests (Table 5) using four different flow rates. Flow rates were adjusted by opening the valve 1/4, 1/2 , 3/4 and 4/4 capacity. For the first step-drawdown test, discharge was measured using a 7 liters bucket and a timer (Q = volume bucket/ time to fill bucket). Discharge rates for the other tests were measured with an online flow meter (Rate/total paddle-wheel flow meter) (Appendix B**)**. In the test done on April 24, 2009, the flow rate was changed every four hours. For the other tests, the flow rates were changed every 24 hours. Step-drawdown data were analyzed using equations (6), (7) and (8). The well efficiency was calculated from a linearized plot of equation 7.

Table 5: Step-drawdown test description

Date	Pumping Rates (m^3/day)
April 24, 2009	84.96 - 410.20
November 21, 2010	115.36 - 327
January, 2011	202.13 – 334.15
February, 2011	91.36 -329.38
April 25, 2011	97.28 – 321.82

Groundwater development cost for the UPRM site based on cost for installation and development of wells, pump well operation (electricity, maintenance), disinfection (chlorination) and connection to distribution system. Cost estimates for connection into distribution system is based on lines cost of pipe, cables, well tops, and other fittings. The cost of well installation was assessed to be the same as the cost of the CP well. For the project, costs were allocated for the pump, pipes, cables, well top and the well installation. Thus, the unit cost per well was $4,400 dollars (Appendix F).

4.3. System Constraints

Having described the system (hydrogeology, water use, water distribution system, etc.) a hydrogeologic-water use model is developed within system and constraints. These constraints are incorporated into the GIS model to make decisions in the feasibility of using groundwater resources for the site, how much to use, number of wells and pumping rates, and location of wells. System constraints are those imposed by the aquifer, water budget (e.g., recharge), well hydraulics, and location of existing infrastructure. GIS model constraints are those that were applied to the system (aquifer and existing infrastructure) and those established for the management of the GIS tool.

Various System Constraints have been identified as follows:

- Water withdrawal cannot exceed recharge rates. Amount supplied for water use is limited by these constraints.
- Drawdown in extraction wells cannot exceed 7 meters (bls). This value provides a conservative drawdown based on the pump location and required hydraulic head.
- Distance between wells at the site is maximized to minimize well interference effects. This distance may be based on the radius of influence or another parameter that may limit the well location.
- Distance between wells and existing water distribution pipeline system is minimized
- Water quality cannot be reduced during pumping.

Various GIS Model Constraints have been identified as follows:

- Areas classified as potential for groundwater development are selected based on the number of wells necessary to satisfy the water use. Several distance-based region are created, depending on the number of wells needed, and the location of the wells are placed within these areas. The location of the well is initially placed at the center of each developed region.
- Determine the location of the centroid of each area selected as potential for groundwater development.

4.4. Well Location

The location of wells in the study area is based on maximizing distance between wells minimizing drawdown and distance to distribution. This was attained using GIS technologies. This method involved preparing the shapefile containing the potential areas for groundwater development, dividing these into five subareas per additional well required, and determining the center for each subarea (Figure 45) by using the GIS tool *ArcTool Box/Data Management Tool/Features/Feature to Point*. This tool creates a feature class (centroid location for polygon features headed by the named FID through 0 to 4) from the input features class (shapefile containing the potential areas for groundwater development). The location of these centers of areas was assigned as the preliminary locations for the needed wells.

5. Results

This chapter presents the development of the hydrogeologic-water use model proposed for groundwater resources management and planning. The model integrates information and data collected and analyzed for the UPRM validation site with groundwater assessment and management using GIS. The objective was to assess the feasibility of supplying the UPRM water use with groundwater resources in the area. If feasible, the GIS model is applied to determine the fraction of water supplied by groundwater, and the optimal extraction plan to minimize extractions impacts (aquifer depletion and/or salt water intrusion).

Hydrogeological data for UPRM, in conjunction with geologic log and interpretation for the site (Abrams, 2010), suggest that the aquifer system is comprised of weathered volcanoclastic and alluvium (Pando et al, 2006, Abrams, 2010). Groundwater in the upper alluvium may occur under water table conditions (Rodríguez-Martínez et al., 2003), but groundwater in the lower zones may occur under confined or semi-confined conditions. Indeed, the pumping and observations wells in the Civil Engineering and Surveying Building (CP, CO, see Figure 12) show water levels above confining (semi-confining unit) and land surface (Figure 14), behave as a confined or semi-confined system. Results of the aquifer and step-drawdown tests performed at the UPRM were analyzed and incorporated into the GIS hydrogeologic model. Aquifer tests provided information on the type of aquifer at the site and the hydraulic properties of the water-hearing formations. Step-drawdown tests provided well hydraulic data for assessment of well productivity and efficiency.

The hydrogeologic model also incorporated estimates of areal recharge and groundwater budget. This budget was compared with water use estimates to assess the feasibility of supplying water from groundwater sources. If so, the fraction of water available was allocated along the number of wells necessary to supply the water and meet the system constraints. The results of the analytical methods used for describing the aquifer and the series of task performed using GIS technologies for providing a rapid tool for selecting the well location and the well extraction details will be discussed.

5.1. Aquifer Characterization

Water level measurements collected at the various UPRM wells (see Figure 12) during aquifer tests show that only the observation well (CO, Figure 18) at the Civil Engineering and Surveying Building is influenced by pumping the Civil Engineering and Surveying Building pumping well (CP, Figure 19). None of the wells located in the CID areas (Figure 20, Figure 21, and Figure 22) show significant changes in water levels during the aquifer tests. Therefore, the CO well the only well for the analysis of the aquifer tests.

5.1.1. Transmissivity and Storage Coefficient Evaluation

Drawdown in the CO well during the aquifer tests show similar temporal behavior and varied between 0.48 m and 0.96 m, depending on the duration of the aquifer test (Figure 18). Drawdown in the pumping well showed some differences in the drawdown magnitudes, and varied between 4.9 m and 6.1 m (Figure 19). Pumping rates varied from 17.09 m^3/hr for the May 9, 2009 to 12.97 m^3/hr for the December 9, 2010 test. The September 25, 2009 had a pumping rate of 15.44 m^3/hr. The lower drawdown observed for the test conducted on December 9, 2010 is associated with differences in initial water levels (bls- below land surface) pumping rates, and pumping well efficiencies (well efficiency is discussed in section 2.4.2)

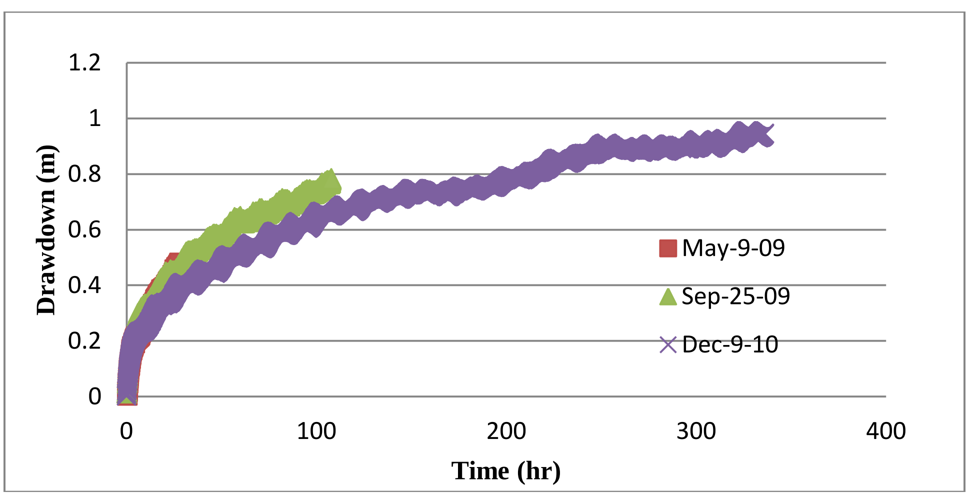


Figure 18: Drawdown measured at the CO observation well

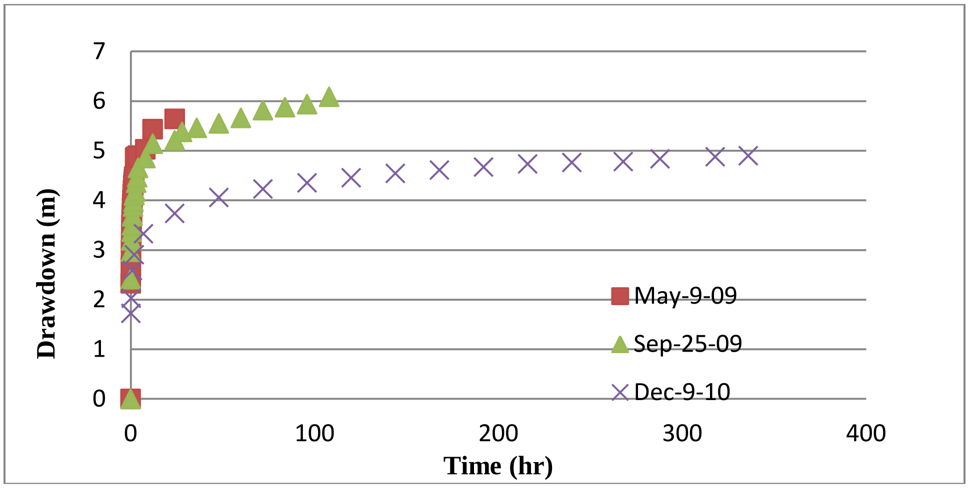


Figure 19: Drawdown measured at the CP pumping well

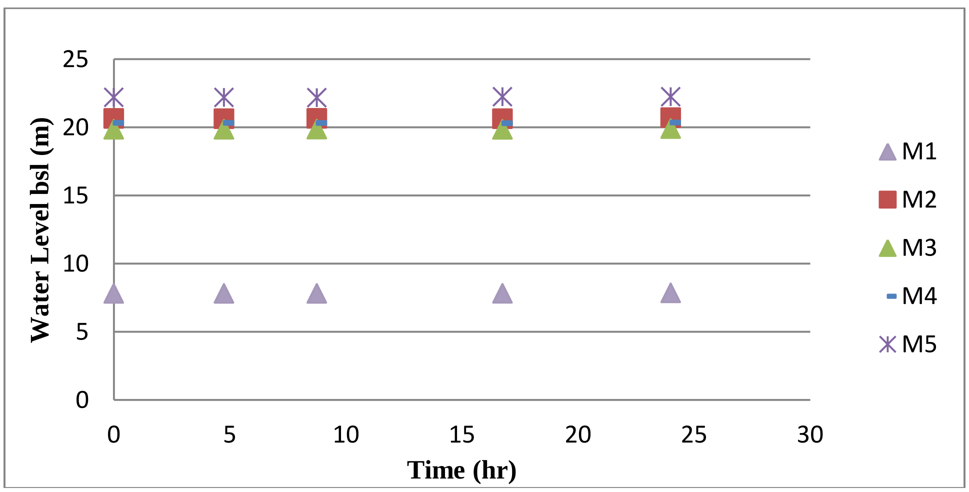


Figure 20: Water levels for the observation wells during the aquifer tests: 24 hrs

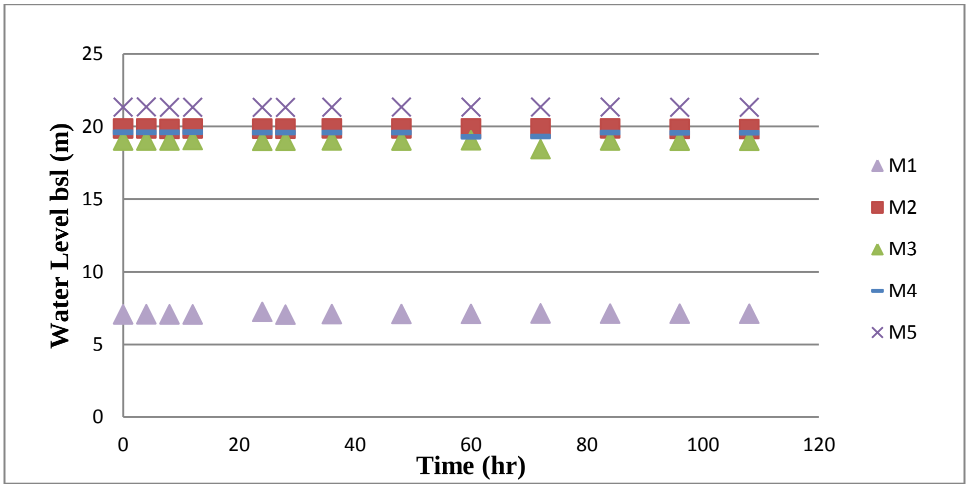


Figure 21: Water levels for the observation wells during the aquifer tests: 108 hrs

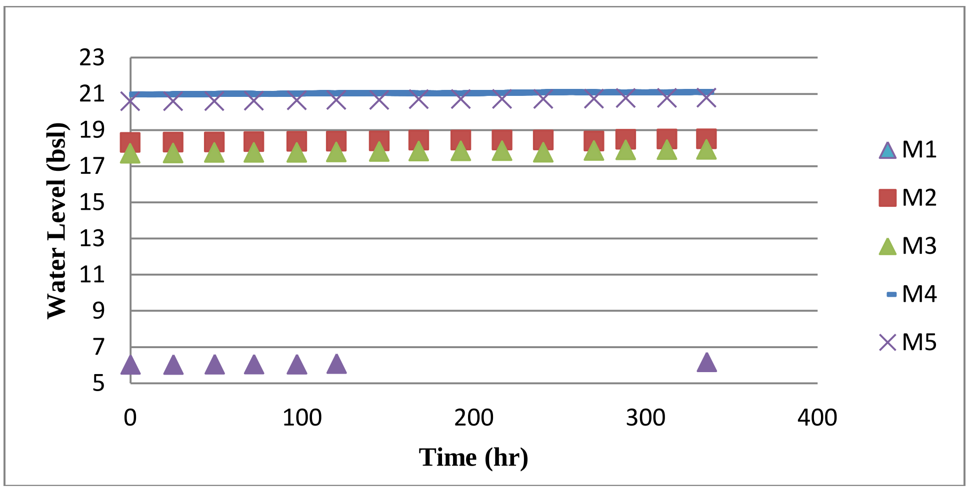


Figure 22: Water levels for the observation wells during the aquifer tests: 336 hrs.

Semi-log temporal drawdown for the observation well (Figure 23) shows a non linear pattern, with changing slope at about 2 x 10^1 hrs after pumping. A steeper slope at the later times reflects a potential proximity to an impermeable barrier (Kruseman and Ridder, 1994). The log-log temporal drawdown test matched well with the Theis curve (Figure 24) and suggests that the system behaves as confined system. Although good matching was found between the data and Theis curve, the Jacob's method (section 2.3.1) was applied for further analysis of the data and determination of hydraulic properties of the system. Jacob's method was used because it was found applicable for the data, and is simpler than the matching method.

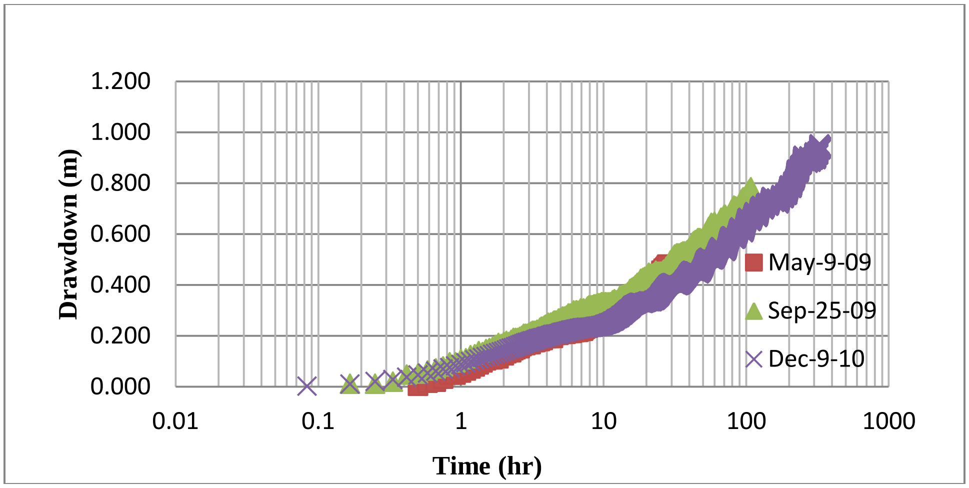


Figure 23: Semi-Log drawdown comparison for CO well

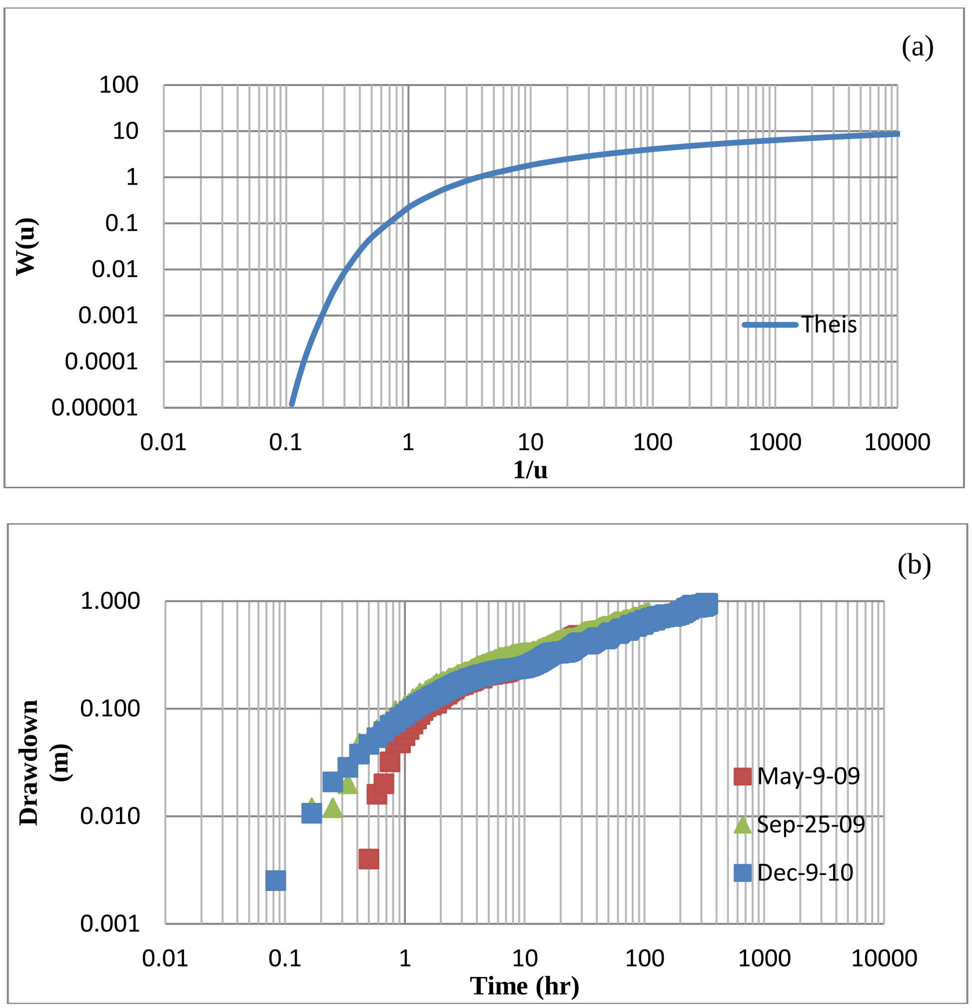


Figure 24: Illustration of (a) Theis Curve, and (b) Log-log drawdown plotting for the observation well (CO)

The semi-log temporal drawdown for the pumping well shows linear conditions at early time with a slight decrease in the temporal drawdown distribution after about 2-4 hrs (Figure 25). The nearly straight line indicates confined conditions with some minimal leakage at later times. Similar to the CO well, the log-log temporal distribution data matched well the Theis curve (Figure 26).

Assuming confined conditions, Jacob's method (section 2.3.1) was used to estimates the hydraulic properties of the aquifer. Even though both drawdown data for the CP and the CO well were collected during the aquifer tests, it is best to perform the analysis using the observation well data instead of data for the pumping well. This is because the observation well is not influenced by well efficiency factors, which affect the response in the pumping well. The semi-log temporal data of the CP well (Figure 23) was divided into early and later response parts (Figures 27, 28, and 29). By applying Jacob's method, each part was thereafter fitted with a linear regression.

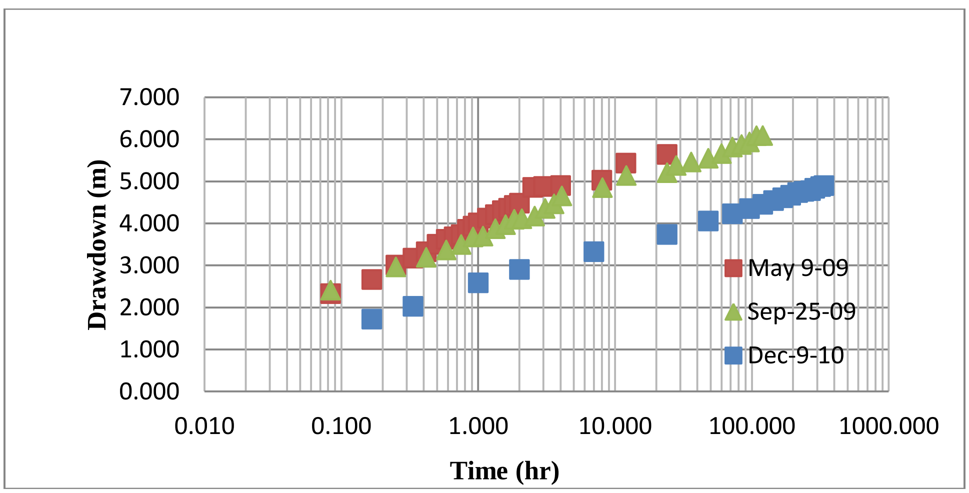


Figure 25: Semi-Log drawdown comparison for CP well

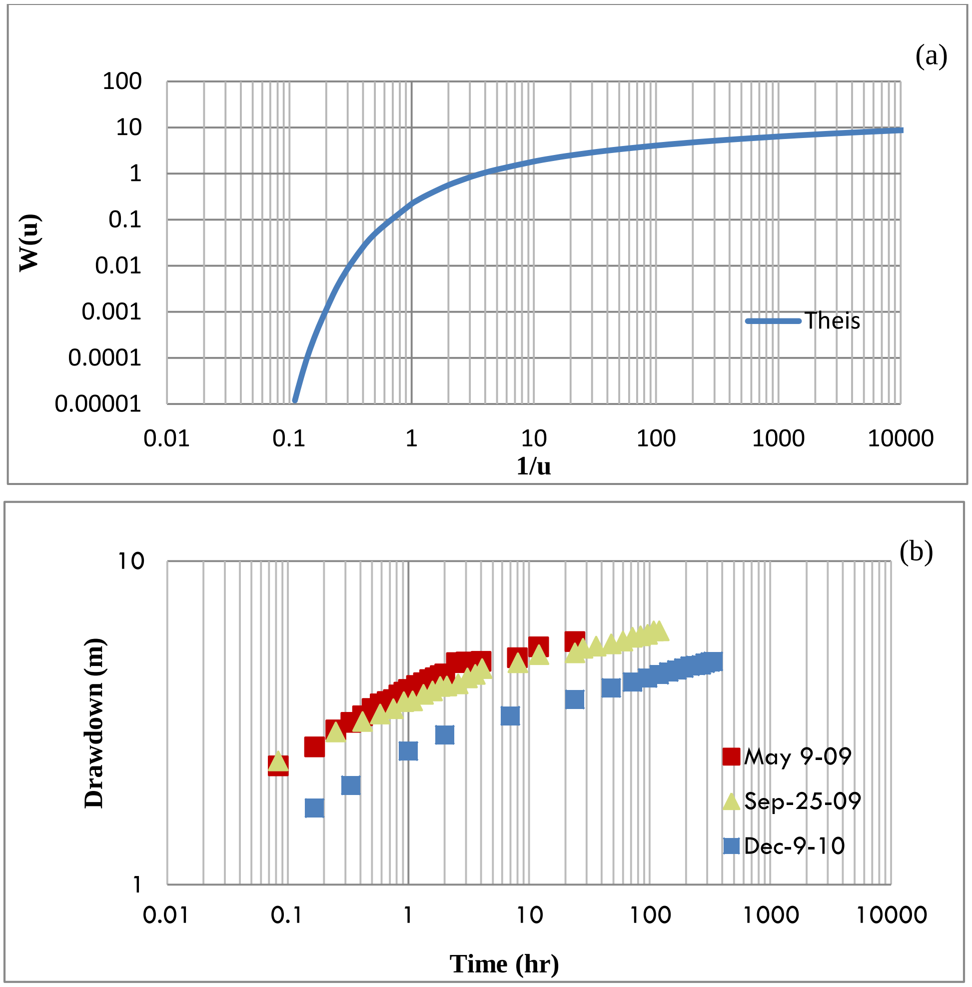


Figure 26: Illustration of (a) Theis Curve, and (b) Log-log drawdown plots for the pumping well (CP)

Transmissivity and storage coefficient estimates (Table 6) were estimated using equations 4 and 5. Early-data values estimates range from 367.55 m^2 /day to 446.83 m^2 /day for the transmissivity and from 0.015 to 0.031 for the storage coefficient (see Table 6). Comparing the values of transmissivity, it is observed that they do not have significant differences. Late data estimates show lower values for transmissivity and storage coefficients. Later data was not considered for the analysis because it does not complied with $\mu < 0.05$ as required by Jacob's method.

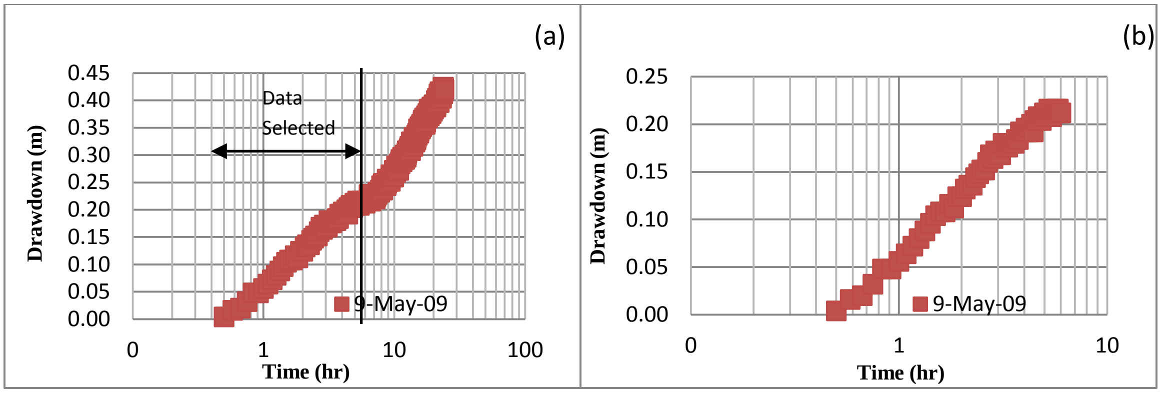


Figure 27: Drawdown data (CO well) for aquifer test: May 9, 2009 (a) complete, and (b) selected data for Jacob's method analysis

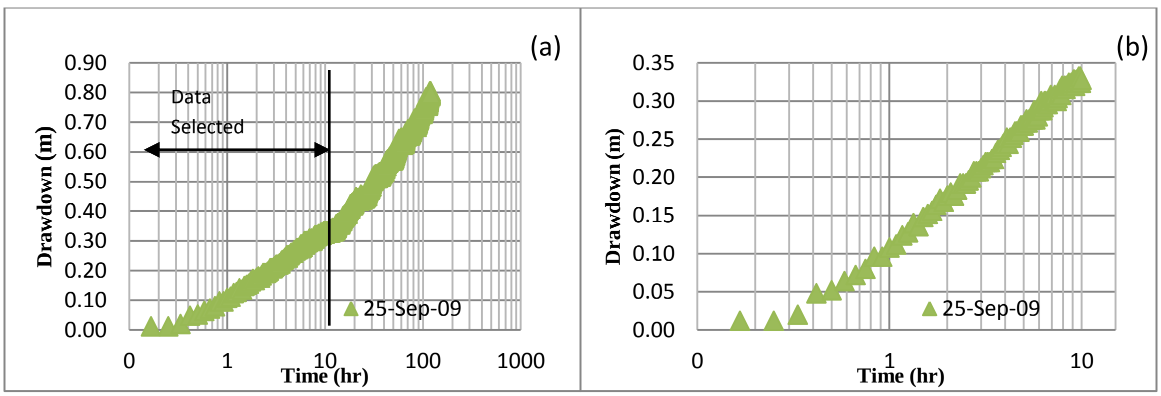


Figure 28: Drawdown data (CO well) for aquifer test: Sep 25, 2009 (a) complete and (b) selected data for Jacob's method analysis

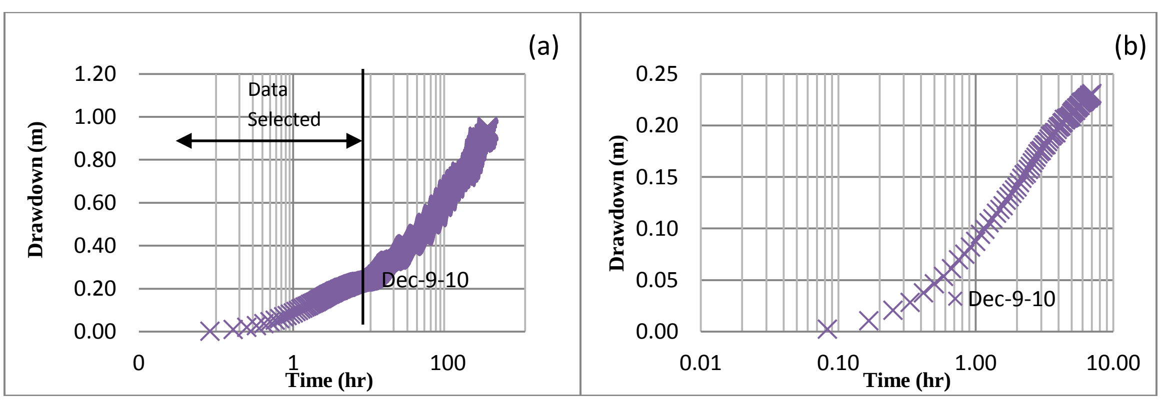


Figure 29: Drawdown data (CO well) for aquifer test: Dec 9, 2010 (a) complete data and (b) selected data for Jacob's method analysis

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Table 6: Hydraulic properties obtained from the aquifer tests for CO well

Date	T	S	Q	
	(m^2/ day)	-	m^3/d	m^3/hr
9-May-09	446.83	0.0031	410.2	17.09
25-Sep-09	338.96	0.0017	370.45	15.44
9-Dec-10	367.55	0.0015	311.31	12.97

A sensitivity analysis was performed using these preliminary values of transmissivities, storage coefficients, and the Theis equation (1). The analysis involved comparison of theoretical drawdown using the estimated transmissivity and storage coefficient with the measured values of drawdown obtained from the aquifer tests (as shown in

Figure **30**, Figure 31 and Figure 32). Values of transmissivity and storage coefficient were varied until the theoretical data best described measured data, as quantified by a root mean square ranging between 0.39 m to 0.73m

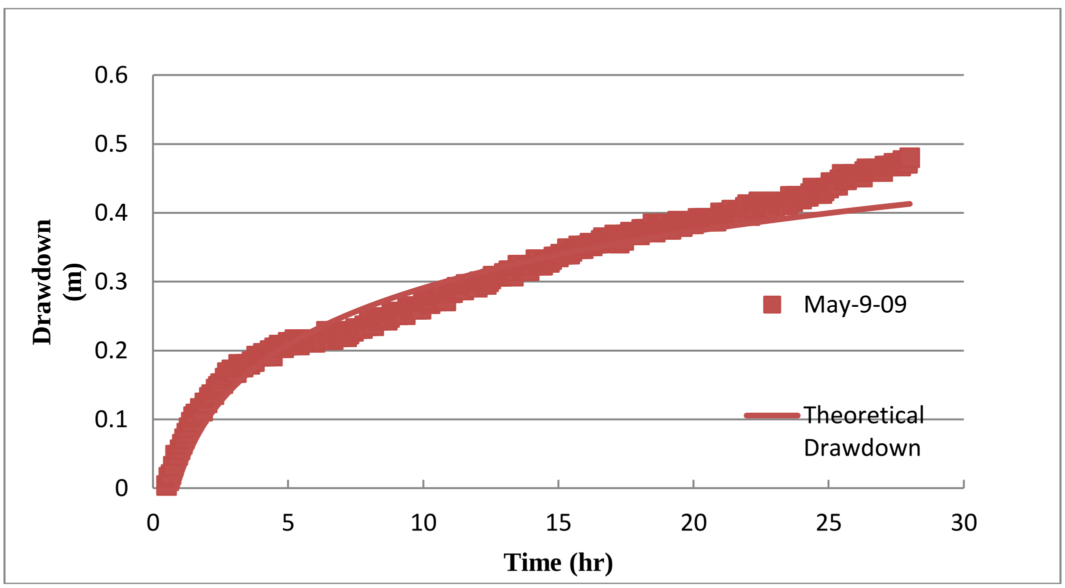

Figure 30: Theoretical drawdown vs. measured drawdown for May 9, 2009 test

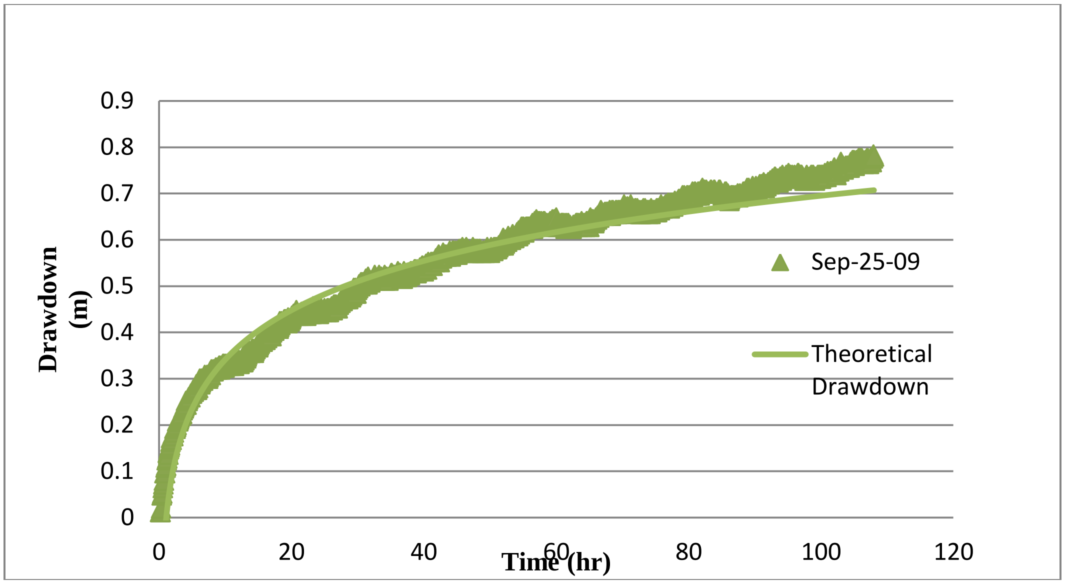

Figure 31: Theoretical drawdown vs. measured drawdown for Sept 25, 2009 test

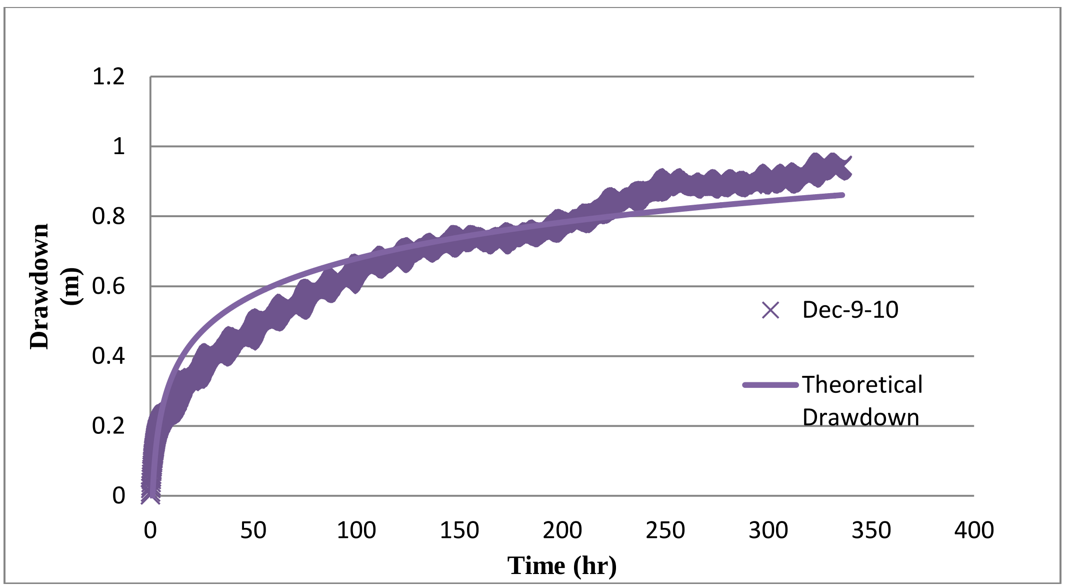

Figure 32: Theoretical drawdown vs. measured drawdown for Dec 9, 2010 test

Table 7 shows the final values of transmissivity and storage coefficient used for adjusting the theoretical drawdown graph in order to be similar to the measured drawdown during the tests. From these values it was obtained an average of 219 m^2/day and 0.003 for the transmissivity, respectively. Note that transmissivity values tend to be lower than those estimated using the Jacob's method (Table 6) but the storage coefficient tend to be slightly higher. This difference reflects the high drawdown at late times and may incorporate the presence of lower permeability barriers in the system.

Table 7: Hydraulic properties values used for best representation of measured drawdown and theoretical drawdown

Date	T	S
	(m^2/ day)	-
9-May-09	300	0.0036
25-Sep-09	192	0.0029
9-Dec-10	165	0.0025
Average	219	0.003

Estimated transmissivity and storage coefficient values (Table 7) were applied in equation (1) to simulate the well hydraulics in the aquifer system of the validation site. Simulated well hydraulics included drawdown and water levels, and the estimation of the radius of influence.

The radius of influence (RI) for the UPRM was estimated 7,742 meters using Jacob approximation (rearranging equation 5) and those average values of transmissivity and storage coefficient. Values ranges between 8,272 and 7,362 m from the pumping well, and extend beyong the study area. It is important to note that even though the UPRM-CID wells (Figure 12) area located between 322 and 507 m from the Civil Engineering pumping well, no drawdown was observed during the pumping period. This suggest absence of hydraulic connection between CID wells and those in Civil Engineering pumping well or presence of flow barrier that can provide water to the Civil Engineering pumping well or prevent expansion of drawdown to CID wells.

5.1.2. Water Evaluation

Another parameter measured during the aquifer test was the water quality. The water quality parameters were measured approximately every 24-48 hours during the test which started on December 9, 2010. Results (Figure 33, Figure 34, and Figure 35) show initial variations (<100 hrs) in chloride (Cl^-), temperature, DO, TDS, SAL, and SpC. Chloride concentrations tend to decrease initially indicating no seawater influence during pumping. Temperatures values nearly fairly constant and Do values tend to increase slightly. TDS, SAL, and SpC increase reach a fairly constant value. The overall water quality parameters suggest negligible effects of saltwater. It, therefore, concluded that water quality does not limit the groundwater resources development.

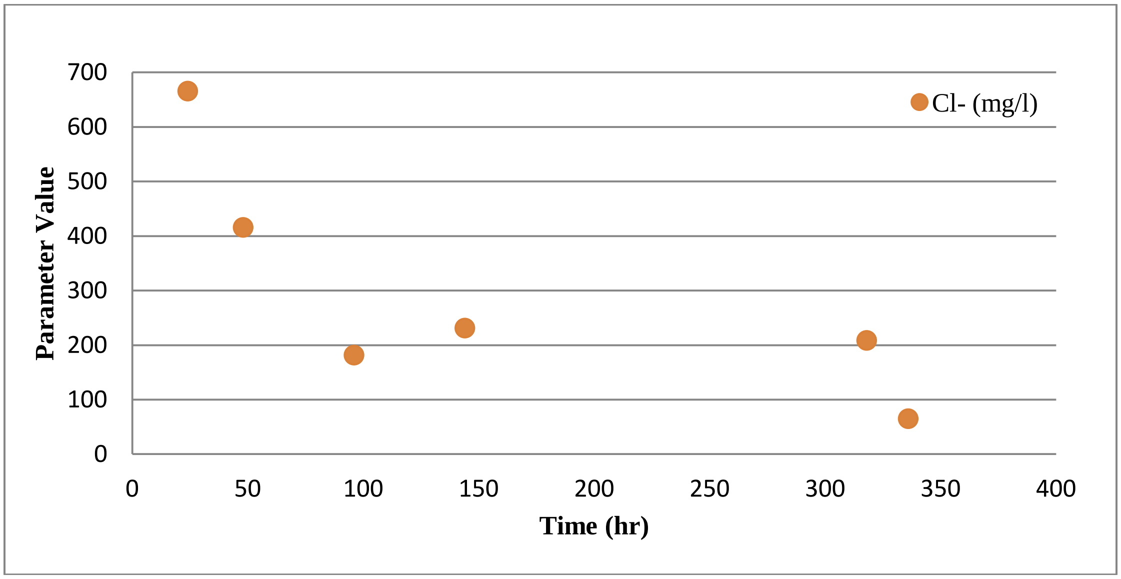

Figure 33: Results for the water quality measurements for CL^{-} during the aquifer test (Dec 9, 2010)

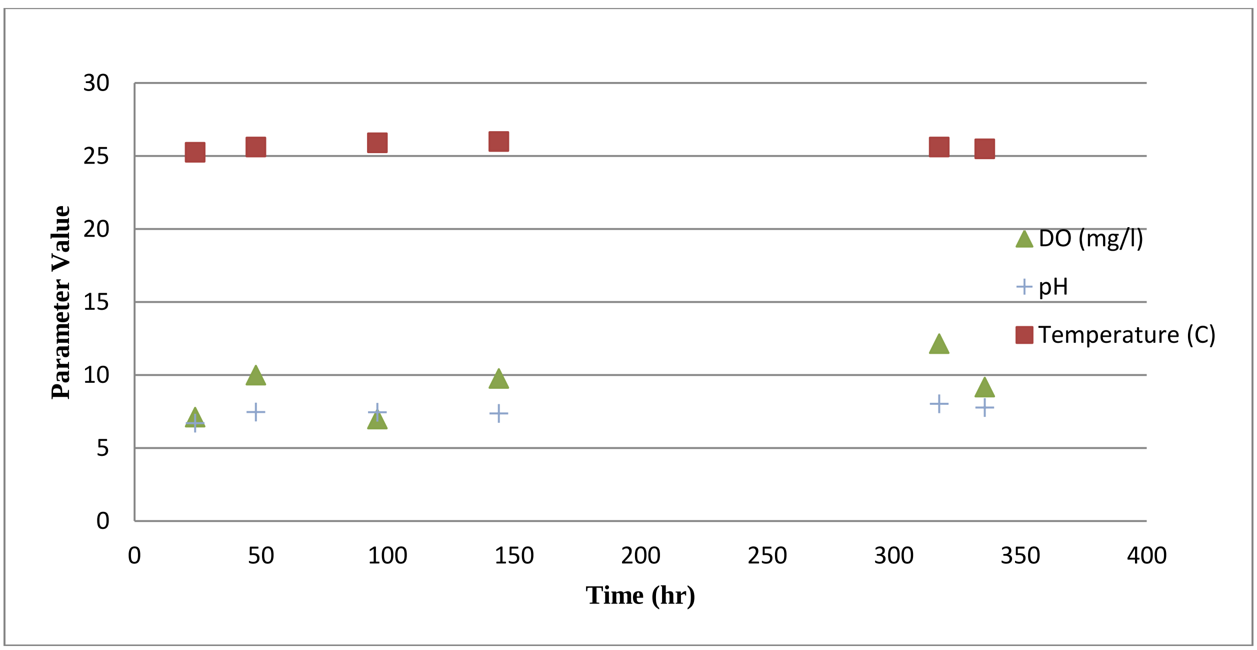

Figure 34: Results for the water quality measurements for DO, pH and temperature during the aquifer test (Dec 9, 2010)

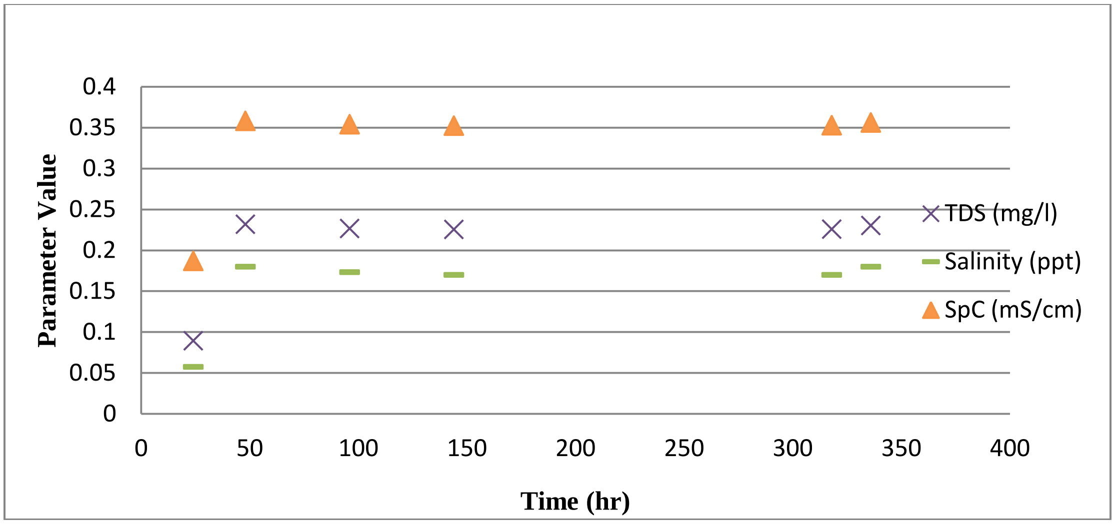

Figure 35: Results for the water quality measures for TDS, salinity, and Specific Conductance during the aquifer test (Dec 9, 2010)

5.1.3. Specific Capacity Assessment

Step-drawdown data collected at the CP well show similar behavior for all test performed (Table 5) as shown in Figure 36.

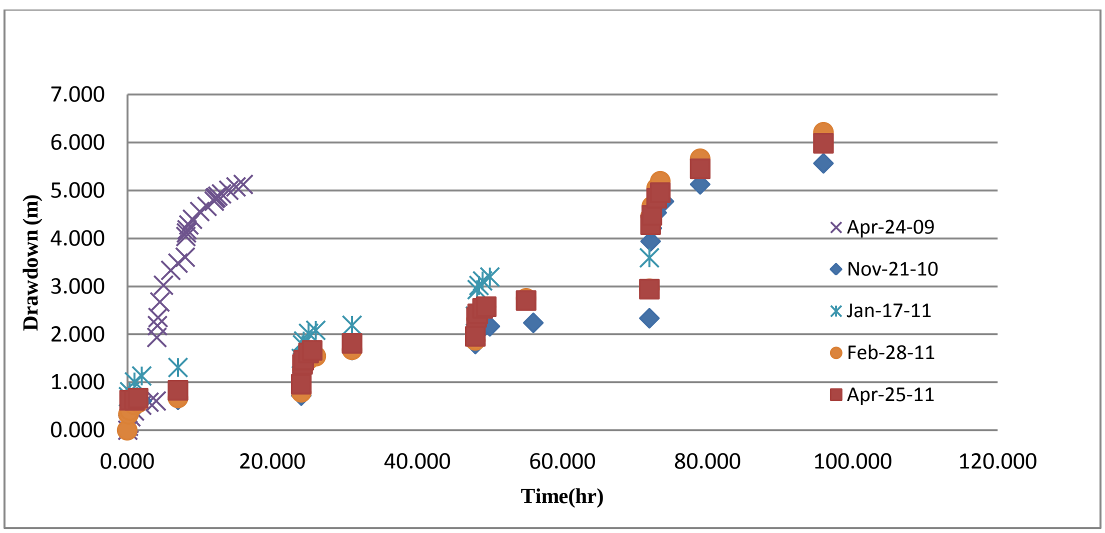

Figure 36: Step-Drawdown Test at CP well

Specific capacity (SC) of the well was determined as the ratio of measured pumping rate and the total drawdown (equation 7) calculated at the end of the flow rate step. A plot of discharge vs 1/SC shows a linear relationship for 2 tests, and a curved relationship for the remaining tests (Figure 37). Earlier step drawdown tests yield linear relationship, but those at later time were curved. Curve relationship may result from non-linear well and aquifer losses typical of fractured rock aquifers (Miller and Weber, 1983), such as the one at UPRM. All test show that SC tends to decrease at higher flow rates (Figure 37). The final specific capacity at the end of each test (inverse value of the ending point of the graph at Figure 37, range from 53.02 to 92.9 m^3 /day-m with an average specific capacity of 67.7 m^3 /day-m.

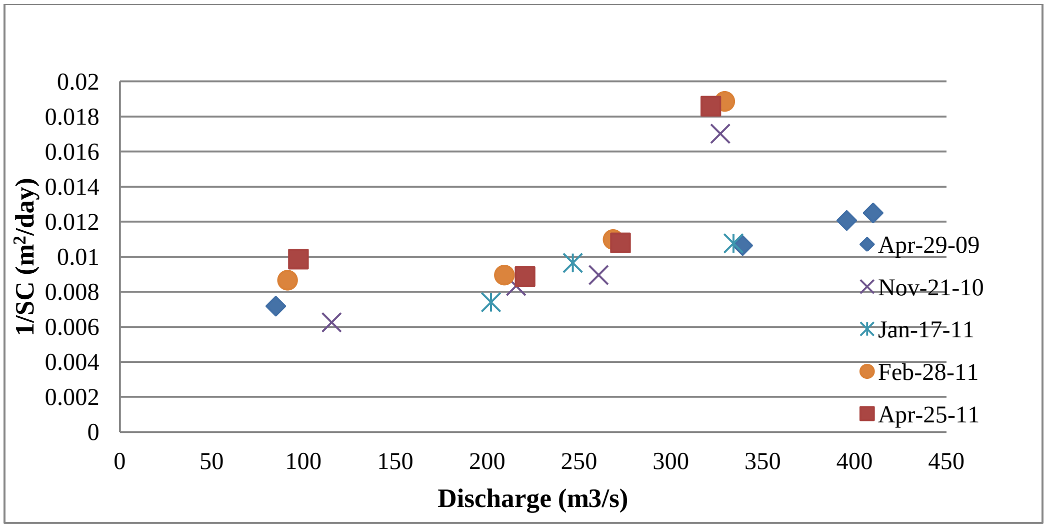

Figure 37: Specific capacity data for the step-drawdown test

Lower specific capacity values at higher flow rates generally translate into lower well efficiencies (Figure 38), which is an expected result due to an increase in the water velocities in the well and possible turbulence near the well. This could be result from the fractured nature of hydrogeologic system. Well efficiency was calculated from theoretical and measured drawdowns. The theoretical drawdown was calculated for every discharge step using equation 3, where the transmissivity and storage coefficient values were obtained using values of the hydraulic properties analysis (Table 7). Theoretical drawdowns were compared to the measured drawdown obtained during the test, to finally calculate the well efficiency using the equation 10.

Well efficiencies in the CP well decreased with increasing discharge and varied from 70% to 28.7%. The efficiencies at the end of the test (higher flow rate) varied 28.7 to 44.89 percent, with an average estimate of 36.3 percent. This might be considered a “poor” well performance indicating that the aquifer system may yield more water than the well can supply.

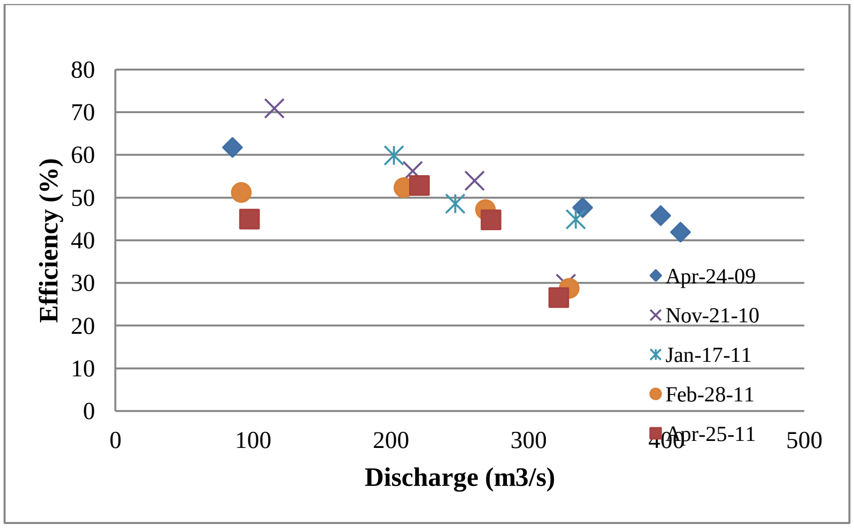

Figure 38: Well Efficiency as a function of flow rate for CP well

5.1.4. Aquifer Recharge Estimates

Recharge estimates from the available literature at the study area range between 0.05 m and 0.25 m/yr, with an average value of 0.15 m/yr (Rodríguez Martínez et al.,, 2003). Two methods were utilized for calculating the recharge: the percentage of the precipitation in the area and water budget method. First method used studies in Puerto Rico that suggested recharge estimates between 5 and 12 % of the total annual precipitation in different regions of Puerto Rico (Puig and Rodríguez, 1993; Quiñones et al., 1994; Graves, 1989). The 9-11% total precipitation for a average total precipitation of 68.7 in at the rainfall station (see Figure 39) located in Mayagüez (station 666073, National Oceanographic and Atmospheric Administration (NOAA)) (Winter, 2009) resulted in recharge estimates rates between 0.15 and 0.20 meters per year, with an average aquifer recharge estimate of 0.17 m/yr. This estimate compares with those estimates from Rodríguez-Martínez et al. (2003).

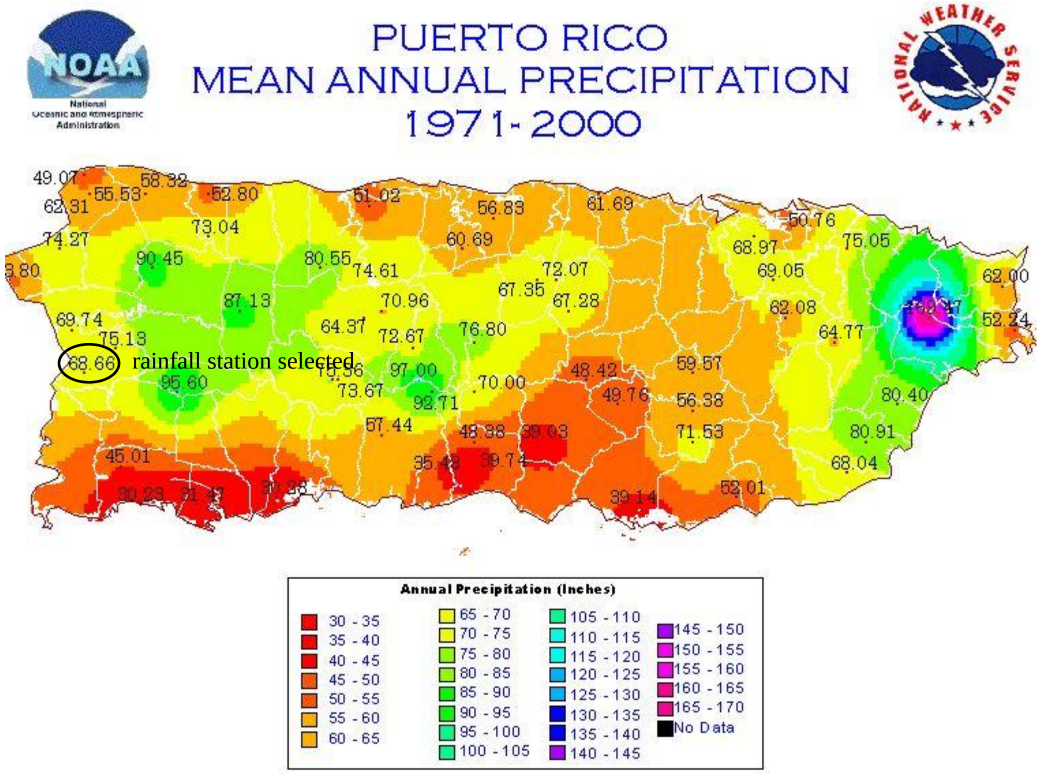

Figure 39: Mean annual precipitation for Puerto Rico (NOAA, 2009)

Recharge was also estimated using the soil moisture budget (Equation 11), which is a type of hydrologic budget method. Figure 40 presents the delineated recharge area that was estimated based on the hydrogeologic terrains MayHT 1 and MayHT3 zones delineations (as shown in green color Figure 40). IT is assumed that surface watershed delineation for Yagüez watershed (shown on pink and green in Figure 40) is similar to the groundwater watershed delineation. The total area of this watershed is 7,098,311.9 m^2.

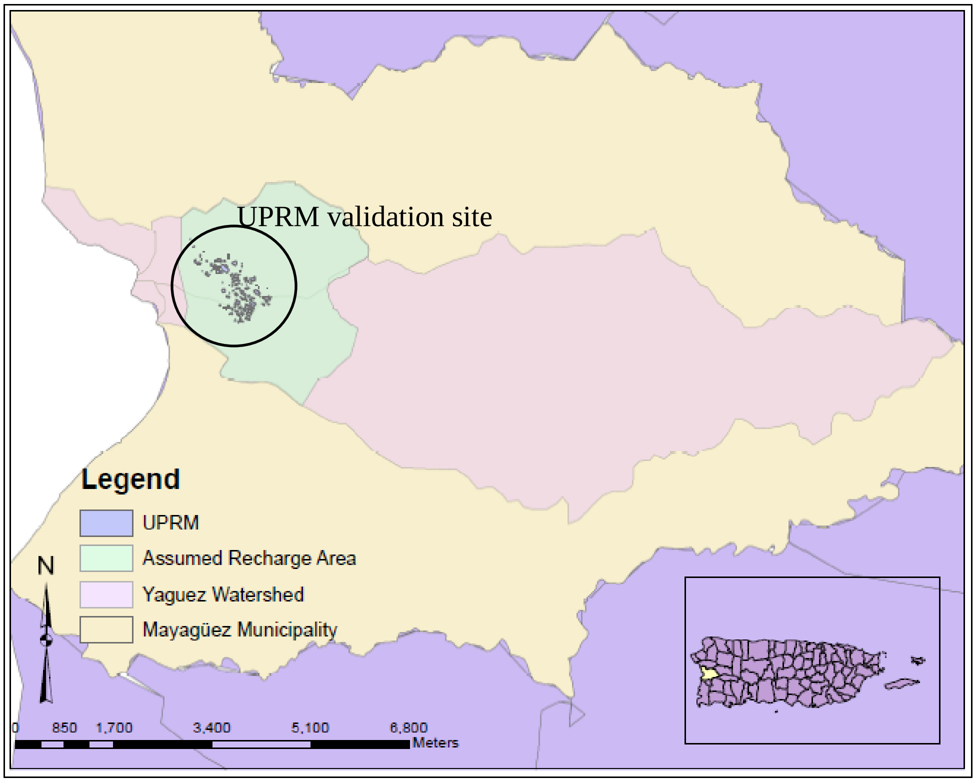

Figure 40: Aquifer recharge area selected for the analysis

Several land use categories exist in the watershed. The percent area corresponding to the land use category (Table 8) shows that agriculture is a major activity in this area (Giovanni, 2007) (Figure 41). Using these data, it was calculated a daily value of actual evapotranspiration for each land use category that later were summed to provide a total daily actual evapotranspiration value.

Table 8: Assumed crop coefficient values for the aquifer recharge area (Giovanni, 2007)

Sector	Land Use Category	Area(%)
1	Forest,shrub, woodland and shede	2.65
2	Pasture	2.72
3	Urban and Barren	12.56
4	Agriculture/hay	81.56
5	Emergent Wetlands	0.61

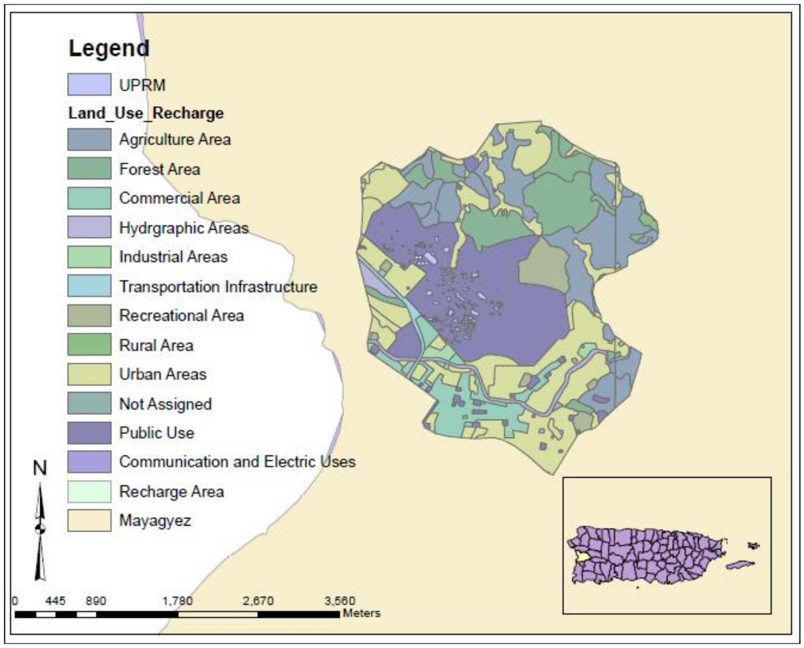

Figure 41: Land use map corresponding to the aquifer recharge area

Figure 42 shows daily values of precipitation, actual evapotranspiration and potential evapotranspiration, according to the method mentioned in section 3.2.5. It may be observed in this figure that there are recharge periods in the system (area between the actual evapotranspiration curve and precipitation peaks in the graph). Annual recharge calculations resulted in values of 0.069 m/yr and -0.20 m/yr for the period of October 1, 2000 to September 30, 2001 and October 1, 2001 to September 30, 2002, respectively. From results only the first period resulted (0.069 m/yr) similar to recharge estimates using 9-11% of an average total precipitation (Quiñones et al., 1995; Martinez-Rodriguez, 2003). The variability in the aquifer recharge estimates using water budget method may results from the broad estimates of rainfall, evapotranspiration, and surface runoff, which yield high margin of error. The negative value (-0.20 m/yr) is not cosidered reliable because the groundwater system does not show declining storage (water levels in the area not declining). For the purpose of this work, it was assumed that the aquifer receive an average annual recharge of 0.17 m/yr over the area. The volume of recharge was calculated as the product of recharge rate and the recharge area. The recharge area over the hydrological terrains was assumed to be similar to the Yagüez watershed area (Figure 40), and was approximate 7,098,311.9 m^2. This estimate yields a recharge volume of 1,235,351 m^3/ yr. In addition, results suggest that the aquifer recharge could come from the aquifer system fractures (Abrams, 2010).

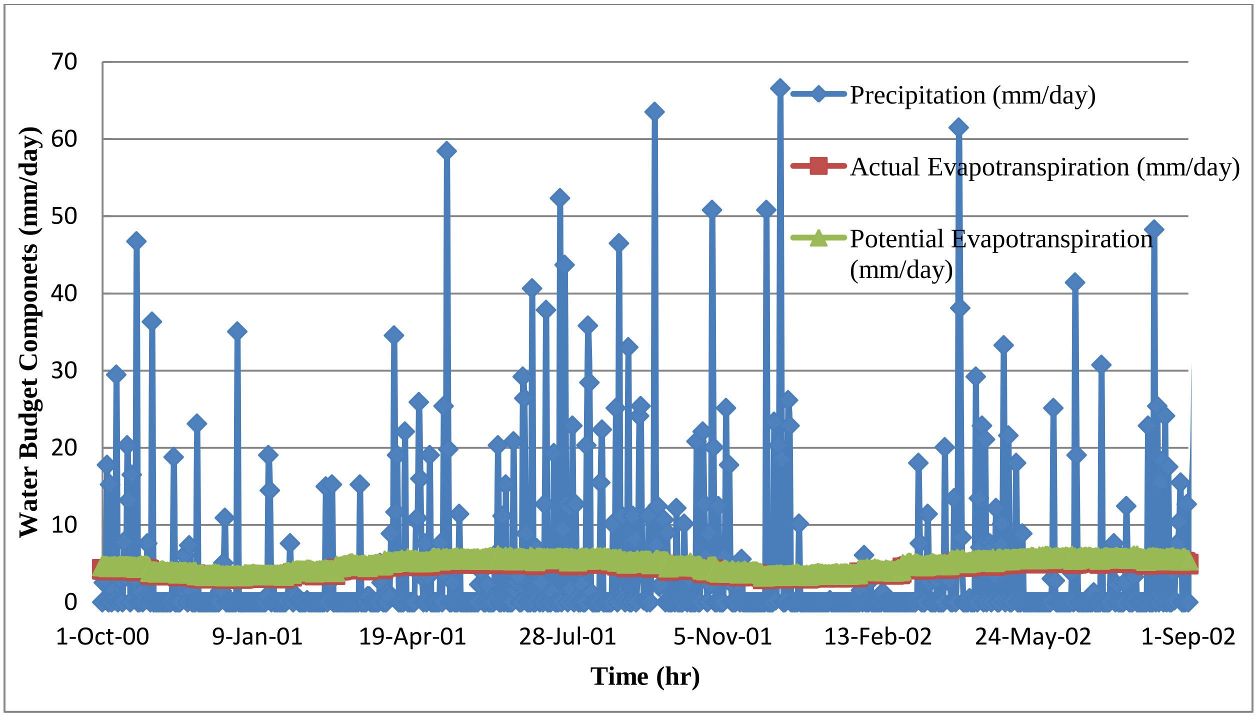

Figure 42: Daily value of precipitation, actual evapotranspiration, and potential evapotranspiration

Figure 43 shows the amount of water remaining on the system after subtractionof runoff (a) and (b) actual evapotranspiration from the daily precipitation. It may be observed in the graphs that there are more negatives values in the precipitation-actual evapotranspiration balance (Figure 43b) than in the precipitation-runoff balance suggesting that evapotranspiration may causing a negative recharge estimates and that it may have been over estimated.

5.2. Hydrogeological-Water Use Model

The last section described the aquifer system characteristics that were used for determining if the groundwater system is able to provide the water use required. The following section discusses the constraints criteria used for assembling the GIS model. The constraints are set to satisfy the scope of the project and also setting an additional scenario in order to evaluate the proposed model.

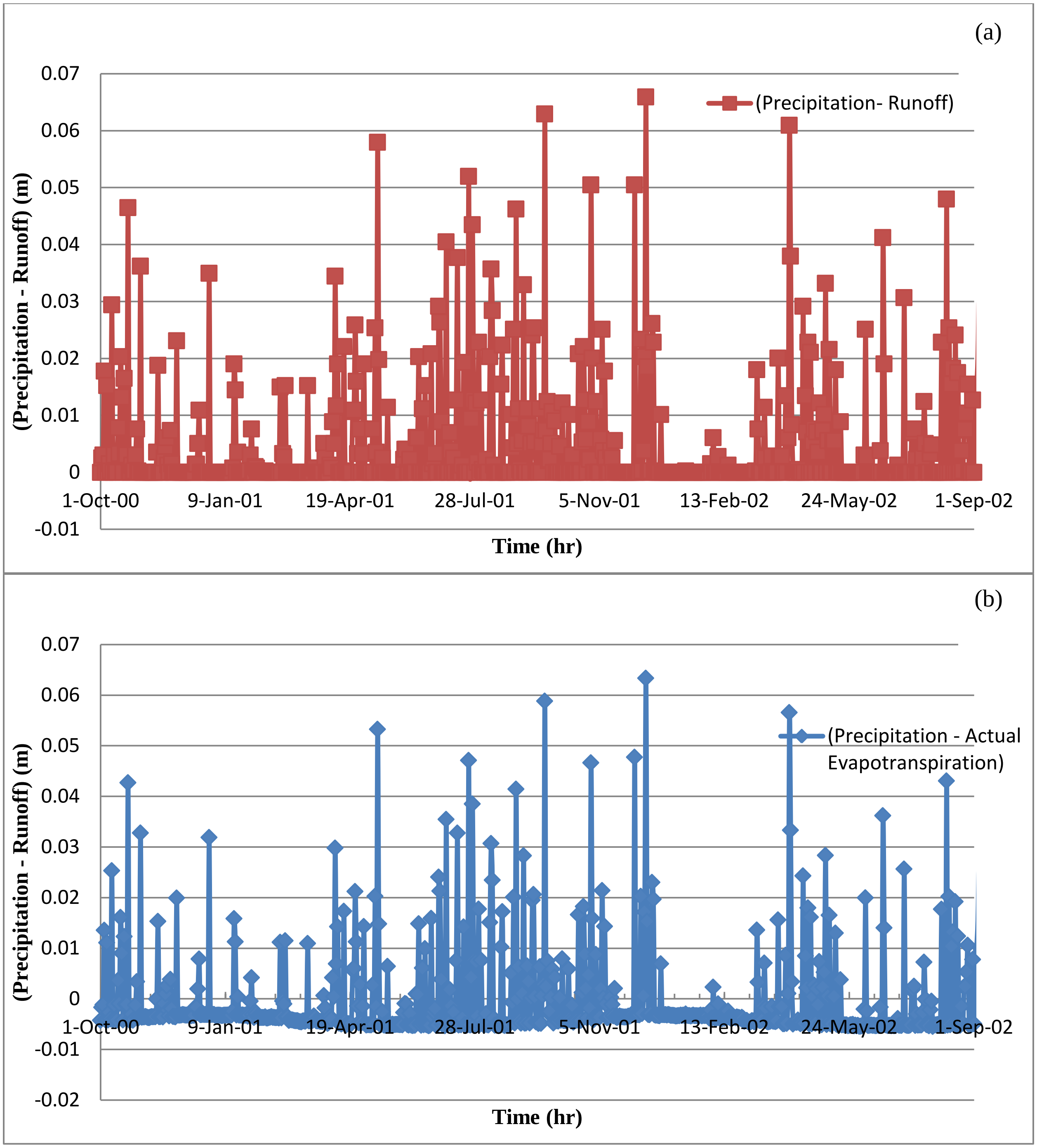

Figure 43:Water remaining after subtracting (a) daily precipitation and daily runoff and (b) daily precipitation and actual evapotranspiration

The number of wells required to satisfy a specific water use is estimated from specific capacity data, subjected to a maximum drawdown constraint. For the validation site, the maximum drawdown is limited to the depth of the water-bearing formation and the depth of the well pump. The depth of the water-bearing formation in the CP well at UPRM is approximately 18m bls and extends to approximately 32 m bls (from well logs, Figure 9). The well pump is located 17 m bls. By using a safety head of 3 m above the pump, the maximum allowable drawdown is 14 m bls. Considering the limitations of information on describing the hydrogeologic characteristics of the UPRM site, a safety value of 50 % was applied and the permitted maximum drawdown was set at 7 m bls. Using an estimated specific capacity of 24,717 m^3/ yr, the maximum discharge that can be extracted from the existing well is 173, 020 m^3/ yr. Comparing this flow rate with the water use rate (208, 379 $m^{3/}$/yr) it can be concluded that at least 2 wells are necessary to satisfy the water use requirements. More may be necessary to meet all system demand and constraints.

The location of wells required is optimized using the GIS model. These wells must be located in the potential areas available for developing groundwater system, and the location should minimize drawdown interference by multiple wells (i.e., wells should be located maximizing the distance between each other) and minimizing distance to the water distribution system. For the validation at UPRM these included all areas except those populated by building, road, structures and restricted green spaces (Figure 44). Once the potential areas for groundwater development are selected, GIS tools are applied to determine the optimum sites for location of new wells that can be used for groundwater supply. Maximum distance between wells minimizes total drawdown caused by well influences and maximizes well production.

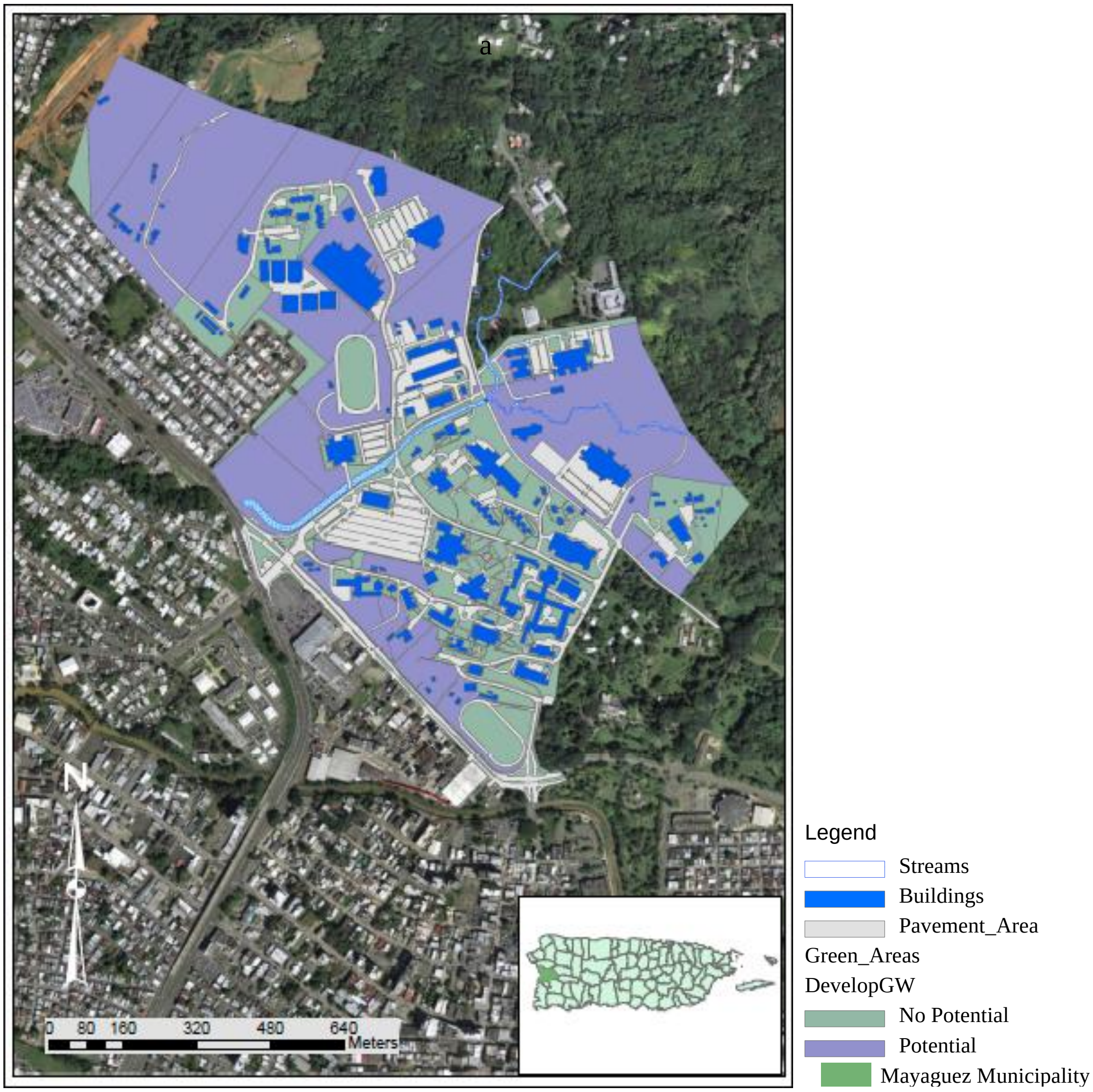

Figure 44: a) Area of study having buildings, roads, restricted green areas, and potential areas for groundwater development (Flores, 2010; PRPB, 2012)

The minimum initial distance between wells is set at the radius of influence of the well. The radius of influence of wells was assumed to be the same for any well within the validation site study area. The radius of influence (approximately 7,742 meters) was estimated for 365 days using hydraulic properties estimates and Theis equation (equation 3) IT is larger than the area of study, but wells must be located in the study area. It was therefore, necessary to maximize well distance within potential areas for groundwater development at the UPRM site.

Because there is an existing pumping well for this project at the study area this well (CP well, see Figure 12) was set as the 1st well, or 1st point to calculate the distance to the other preliminary wells locations. In practice, any point can be used to begin the iteration. Even though only one additional well is needed, more than on subareas are evaluated to maximize distance between wells, and minimize distance to distribution lines. For one additional well, 5 subregions are created, and the centroid of each area is established as a potential well location (Figure 45). Distance between wells was calculated using the *ArcTool Box/Analysis Tool/Proximity/Point Distance* which provides a table (Table 9) containing the distance from the existing pumping well (CO well) to the preliminary wells location previously named "FID" (in this new table is named NEAR_FID) as shown in Table 9. Points with a distance higher than 500 meters were selected for the study, although in principle should depend on the radius of influence. This distance was based on the observation that the UPRM-CID wells were located at 500 m from the Civil Engineering pumping well (CP), and that no drawdown was measured in these wells during the aquifer test. Points 0, 1, 3 and 4 (Figure 45) were those that complied with the 500 m distance criteria. Even though that only one additional well is needed, more than one may be looked in the event that the first one is not located near to the existing pipeline distribution system or that estimated drawdown caused by multiply well influence require additional wells.

For the four preliminary wells locations, GIS tool and the *ArcTool Box/Analysis Tool/Proximity/Near* calculate which one of the wells locations (NEAR_FID equal to 0, 1, 3 and 4) is the nearest to the pipeline distribution system. The results showed that the well named NEAR_ID 1 accomplished the constraint of being closest to the existing infrastructure. This location was selected for the additional well required for the water use. The two proposed wells, therefore, include the existing pumping well, CP (located at the Civil Engineering and Surveying Department named CP well) and the new well suggested after considering the constraints criteria (Figure 46).

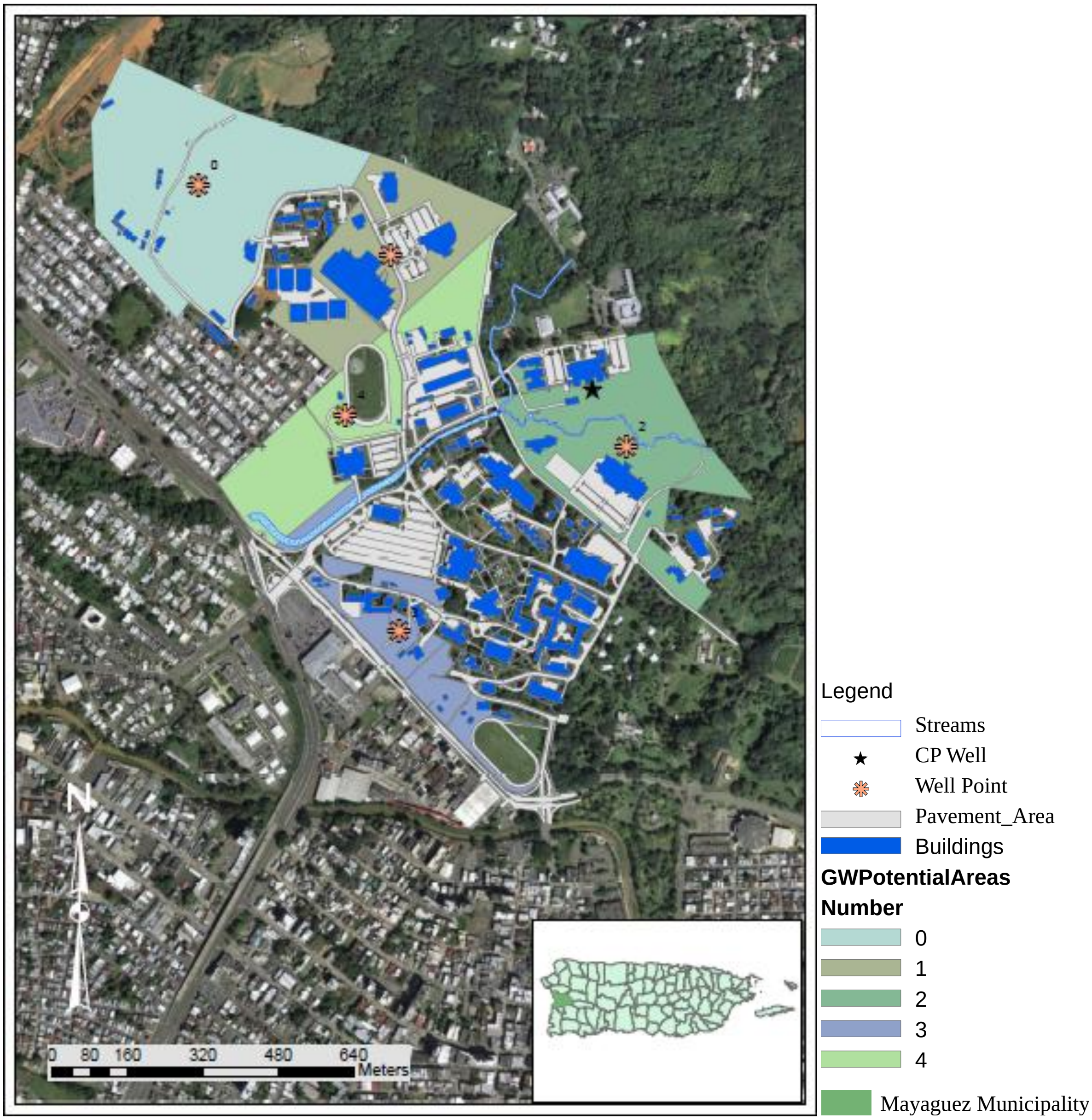

Figure 45: Center locations (preliminary well point locations) without including CP well

Table 9: Distance from the CP well to the proposed pumping wells and water distribution lines

Number	Name of each possible well location (NEAR_FID)	Distance from CP Well (m)	Distance from pipeline to possible well location (NEAR_DIST)
1	0	941.43	171.94
2	1	514.24	7.67
3	2	140.53	24.54
4	3	656.60	54.88
5	4	525.88	72.39

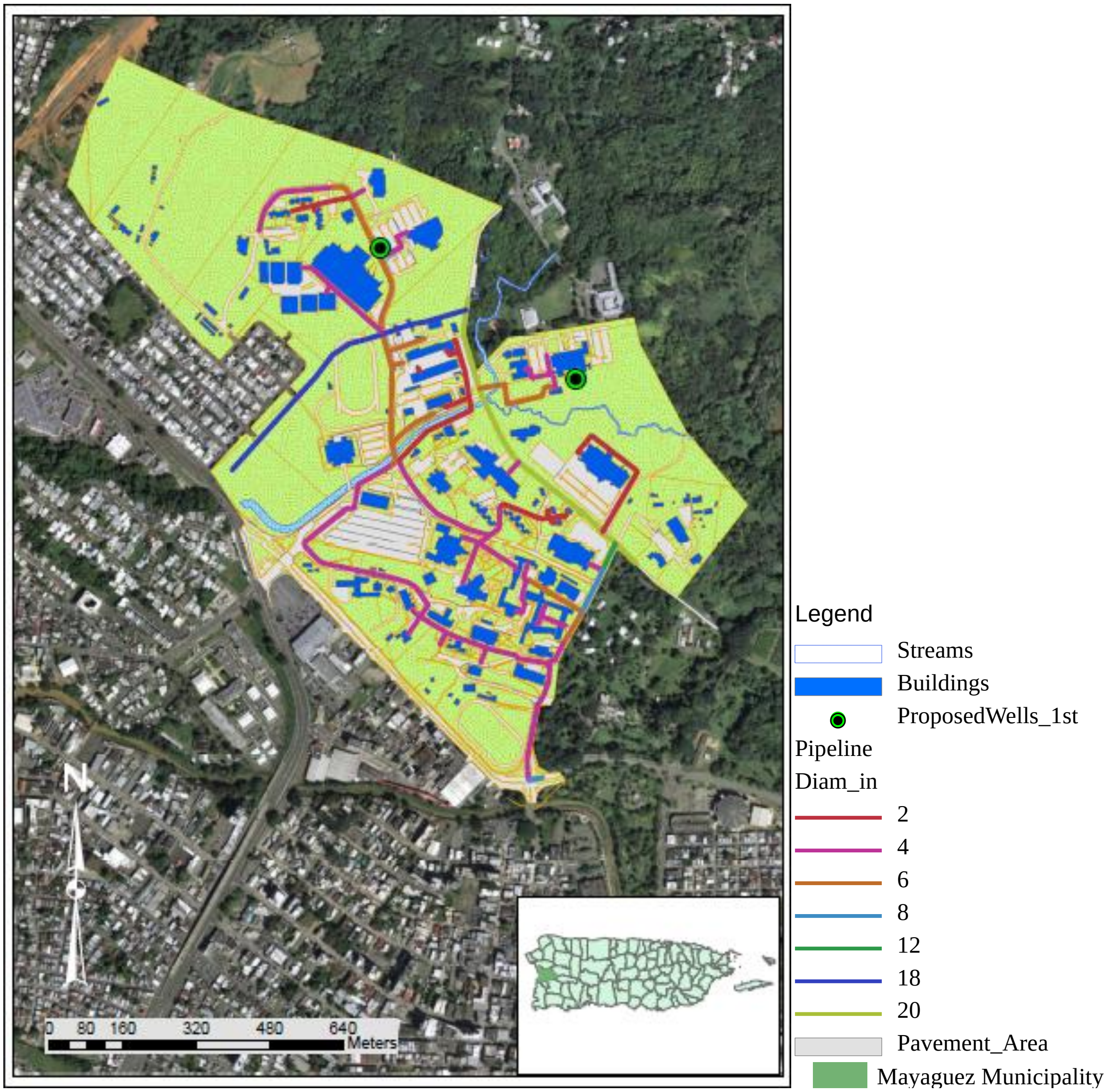

Figure 46: Location of the final proposed wells system

Having determined the locations for the possible wells and knowing the hydraulic properties of the aquifer, the total drawdown at the end of 1 year of constant pumping caused by each well is calculated using equations 2 and 3 and hydraulic properties given in Table 7. Table 10 shows the parameters used to determine the number of wells necessary and the total drawdown caused by them. It also shows the distance $r_{nj,}$: n represents the well from where the distance is measured and j represents the well to where the distance is measured. The total drawdown caused by the two wells (drawdown at pumping well (CP) + drawdown cause by the distant pumping well) equals to 9.78 meters. This total drawdown exceeds the allowed drawdown of 7 m, and requires lowering the discharge rate per well from 173,020 to 118,625 m^3/yr. This reduction in the discharge rate resulted in a total drawdown equal to 6.70 meters which is below the permitted value and still provides the water use (118,625 m^3/yr per well).

Table 10: General parameters used for the existing site validation conditions

Maximum drawdown allowed (m)	7
Transmissivity (m^2/yr)	79,935
Storage Coefficient	0.003
Water Use (m^3/yr)	208,379
Specific Capacity (m^3/yr-m)	24,717
Maximum discharge rate allowed (m^3/yr)	173,020
r11 = r22 (m)	0.08
r12 = r 21 (m)	514.24

Note: r_{ii} is the well radius and r_{ij} are the distance from the new proposed well to the existing pumping well (CP), respectively

5.2.1. Cost estimates

To minimize capital cost of groundwater development, it is necessary to estimate the cost of the proposed system. It is assumed that the cost entails: capital cost and operational. Capital cost include: well construction and development (Herman and Jennings, 1996), well pump, extension of pipe system for connecting into existing water distribution system, and valves and fitting (Campos, 2004). Estimated cost for these items is given in Table 11. Also included is the cost of a storage tank (optional) (Norwesco Tanks, 2012) and maintenance cost (Economic Co-operation and Development, 2012). A 570 m^3 storage tank is suggested to provide one day if the system fails. Electricity cost is estimated at approximately $ 0.26 kwatt/hr (AEE, 2012) using a pumping time of 24 hrs and a pump consumption of 1.5 kwatt/hr (MidAmerican Energy, 2012). Only chlorine is used for water treatment (Well Water Chlorination System Options, 2012), as his is the only treatment required for groundwater wells (EPA, 2006). Because UPRM is a public institution, it would not incur in payment of water extraction (0.2¢./gal required by the Department of Nature Resources of Puerto Rico) (Department of Nature Resource of Puerto Rico, 2000). Regarding to the annual cost of using water supplied by the PRASA, the cost of the groundwater system is minimal, and the initial investment would be paid in 5 month.

Table 11: Cost estimates for groundwater development

	Item*	Per Well	For 2 Wells
Capital Cost	well construction and development[1]	$8,160	16,320
	well pump[1]	$3,000	6,000
	pipe ($ 3/ft)[2]	$1,040	$1,320.00
	valve and fitting[2]	$3,480	$6,960.00
	storage tank,8 tanks @ 20,000 gallons (accessories not included)[3]	$160,000	$320,000
Operational Cost	Electricity (yearly)[4]	$6,833	$13,666
	well maintenance and testing (yearly)[5]	$5,509	10,996
	Treatment (chlorine)[6]	$2,050	$4,100
	Total	$190,100	$379,417

*Based on cost estimate for: [1] 2004 provided by Campos Drilling (Campos, 2004); [2] 2012 (Grainger, 2012); [3] 2012 (Norwesco Tanks, 2012); [4] 2012 (AEE, 2012); [5] 2012 (Economic Co-operation and Development, 2012), and [6] 2012 (Well Water Chlorination System Options, 2012).

5.2.2. Additional Scenarios

An additional scenario was performed to assess the effect of lower specific capacity values in the area. Lower specific capacity impacts the number and location of wells. For this scenario (name 2nd scenario), a specific capacity of 7300 m^3 / yr-m is used. All other hydraulic properties and system constraints were assumed to be the same as the previous scenario.

Results showed that for a maximum drawdown of 7 meters and a specific capacity of 7,300 m^3 / yr-m, each well would have a maximum pumping discharge rate of 51,100 m^3 /yr. To satisfy the water use, a total of 4 wells must be addedl to the existing well CP. With this number of wells, the potential areas for groundwater development were divided into 20 subareas (Figure 47, 5 subareas additional per additional well). The locations of the centers for each subarea were determined and named as FID from 0 to 19 (Figure 47).

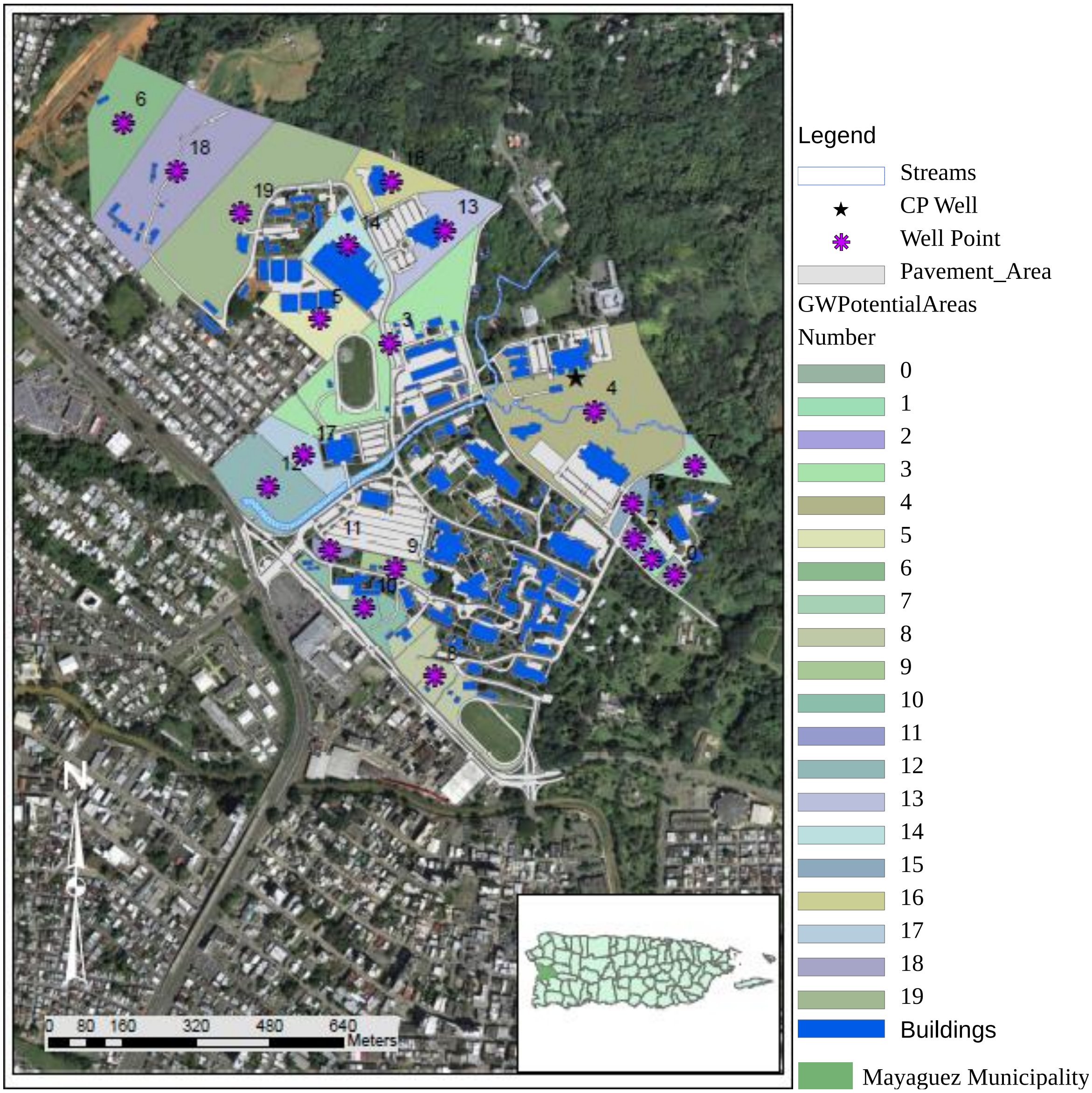

Figure 47: Preliminary locations of wells for the second scenario without including CP well

The possible locations for the wells system were determined and the distance from the CP well to the other center point of each subarea (headed by the name NEAR_FID, Figure 47 was calculated. The subareas to which the center point distance to the CP well was higher than 500 m meter were selected. Those were points 9, 5, 14, 16, 17, 11, 10, 12, 8, 19, 18 and 6 (distance in ascending sort) points named under the NEAR_FID (Table 12). Those points that were closer to the water distribution system were thereafter selected. The closest four points to the distribution system were points 9, 11, 19 and 14. The additional 4 wells locations were selected at 570.77 m, 654.85 m, 811.94 m and 573.72 m from CP well (Figure 47 and Table 12) for the 2nd proposed scenario.

Table 12: Results for the second scenario calculations using GIS tools

Number	Name of each possible well location (NEAR_FID)	Distance from CP Well (m)	Nearest distance from pipeline to possible well location (NEAR_DIST)
1	0	482.99	88.91
2	1	430.42	33.45
3	2	376.58	31.27
4	3	410.81	9.76
5	4	84.43	48.54
6	5	571.26	64.73
7	6	1129.87	359.09
8	7	322.98	124.47
9	8	719.05	72.84
10	9	570.77	18.43
11	10	680.62	80.41
12	11	654.85	24.44
13	12	709.40	86.50
14	13	429.07	82.00
15	14	573.72	53.11
16	15	302.74	28.19
17	16	585.23	62.26
18	17	616.51	98.20
19	18	977.82	208.21
20	19	811.94	46.44

Total calculated drawdowns in this 2nd scenario were estimated by applying the general parameters shown are in Table 13. Similar to the 1st scenario, the effect of pumping a well on the other wells is obtained by applying the principle of superposition (MacMillan, 2009) as a function of distance. Total drawdown on each well is the addition of the drawdown caused by the well's own pumping, and those caused by the pumping of the other wells at a distance from that well. Distance among the different well pairs is given in Table 13.

The results showed that using four additional wells to the CP well (total of 5 wells) causes a total drawdown of 10.91 meters. This total drawdown exceeds the maximum allowed drawdown. To decrease total drawdown and maintain the same supply, an additional well was added and the discharge rate per well decreased 51,100 to 41,975 m^3/ yr. The location of the additional 6th well was selected according to the constraints criterion of maximizing distance from the existing well (CP) and minimizing distance to the water distribution system. The well point under FID equal to 16 was selected from the list (Table 13). The total drawdown value for this was estimated at 10.00 meters which is higher than the maximum allowed drawdown (7 meters).

Table 13: General parameters for 2nd of the hydrological-water used model at the validation site

Maximum drawdown allowed (m)	7
Transmissivity (m2/yr)	79,935
Storage Coefficient	0.003
Water use (m3/yr)	208,379
Specific Capacity (m3/yr-m)	7,300
Maximum discharge rate allowed (m3/yr)	51,100
r11 = r22 (m)	0.08
r12 = r21 (m)	577.77
r13 = r31 (m)	654.85
r14 = r41 (m)	811.94
r15 = r51 (m)	573.72
r16 = r61 (m)	585.23
r17 = r71 (m)	571.26
r23 = r32 (m)	147.57
r24 = r42 (m)	842.36
r25 = r52 (m)	710.88
r26 = r62 (m)	842.27
r27 = r72 (m)	565.92
r34 = r43 (m)	760.16
r35 = r53 (m)	667.34
r36 = r63 (m)	816.45
r37 = r73 (m)	504.77
r45 = r54 (m)	243.14
r46 = r64 (m)	336.86
r47 = r74 (m)	287.76
r56 = r65 (m)	169.02
r57 = r75 (m)	173.07
r67 = r76 (m)	339.55

Note: r_{ii} is the well radius and r_{ij} are the distance from the new proposed well to the existing pumping well (CP).

Observing that there was no significant reduction in the drawdown after reducing the discharge rate and adding a new well point, another well was added and the discharge rate per well was reduced to 32,850 ^{3}/yr, which is the minimum discharge rate that can be applied to the pump (pumping well CP) without damaging the device. The well point corresponded to the FID #5 (Table 13).

The estimated total drawdown resulted from the additional 7th well was estimated at 10.03 meters, which is similar that adding only the 6th well point. This indicates that adding well, even at lower pumping rates results in no significant reduction in drawdown in the system. Because there is a safety measure in this constraint, it may be possible to allow higher drawdown. The higher capital and operational cost, however, does not justify the lower productivity of the system.

Figure 48: Final wells location for the second scenario

A 3rd scenario simulated having a total of 5 wells (same as scenario #2), but pumping at a rate that satisfy the maximum drawdown constraints, but not necessary the total water use.

This resulted in a discharge rate of 164,250 m^3/yr (32,850 m3/yr per well) which corresponds to approximately 80% of the water supply required for the existing water use demand.

In case that the water use cannot be satisfied, groundwater can be used to supply water to some areas. Selections of these areas are made based on their proximity to the water distribution system (i.e., areas or buildings closest to the distribution lines are initially selected). The total water use for those area/buildings is also taken into consideration. A layout of the land use (building, etc.) and the total annual water use is shown in Figure 49 for the UPRM site. By overlaying the location of potential new well in this map, it can be observed that wells system is closest to the Civil & Chemical water meter, Physic water meter, CAAM Pool water meter and the Alzamora water meter. The total water use corresponding to these water meters is approximately 114,000 m^3/yr and it is within the range of water amount that the wells system can provide. Hence, if the 2nd scenario is applied it is recommended that groundwater partially provide the water use required for those areas, and that the rest of the buildings receive water from the Biology, La Vita, Chemistry and the CID water meters, which still need to obtain water from the PRASA system. Even though the Pool water meter is located near the well's system, it was not selected for water supply from the groundwater system because at this stage of the project there was no available water use information from this structure.

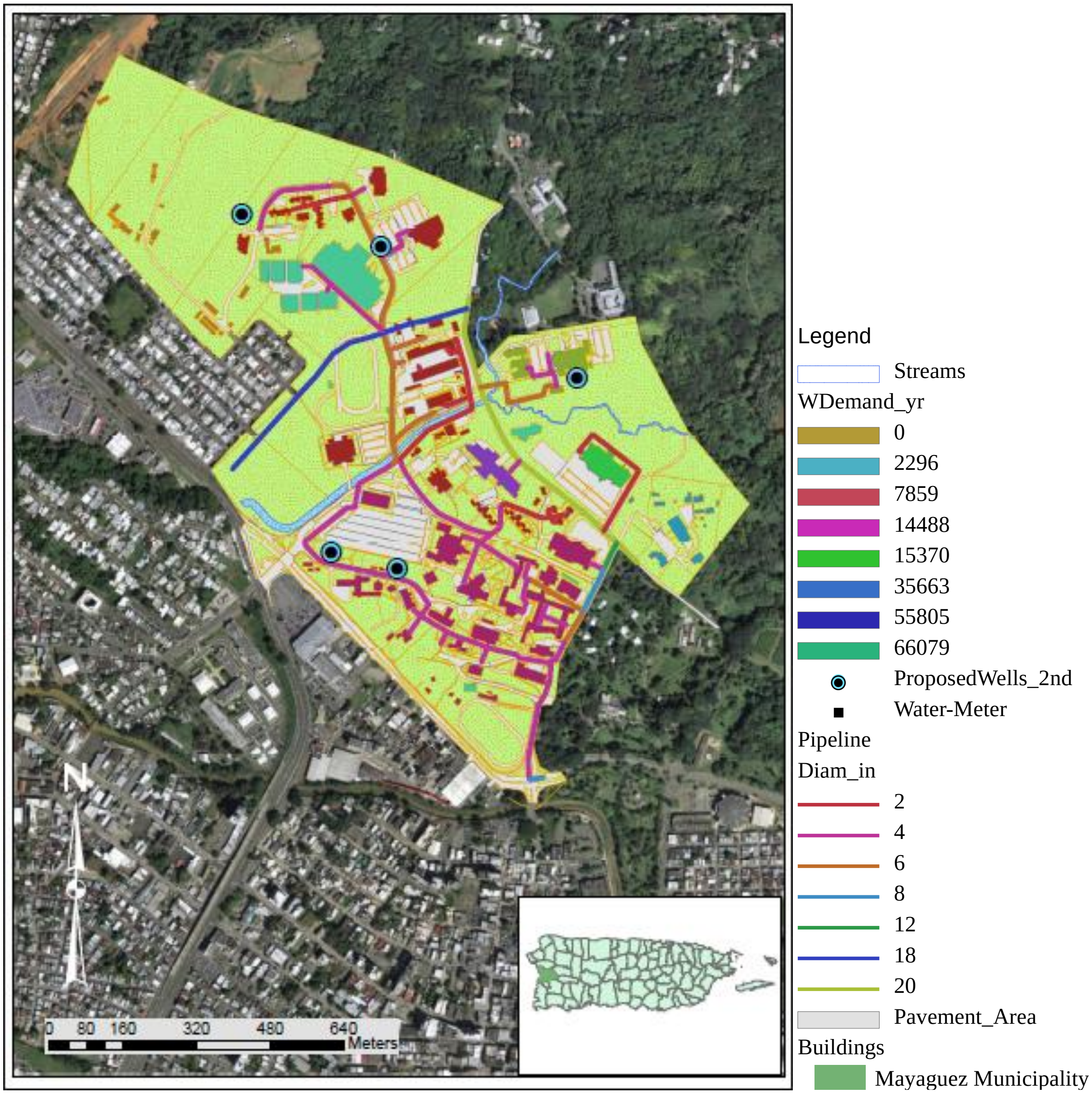

Figure 49: Annual water use according to the water meters measures

The cost estimates for this 2nd and 3rd scenarios is provided in Table 14. The cost is considerable higher than scenario 1, but is still much lower than the currently expenses incurred (monthly average cost of $73,000) for water by the institution, and would be much more reliable. The system can be designed so that interruption in a well does not disrupt water supply in the system.

Table 14: Cost estimates for the 2nd and 3rd scenarios

	Item	For 5 Wells ($)
Capital Cost	well construction and development[1]	40,800
	well pump[1]	15,000
	pipe ($ 3/ft)	330,840.00
	valve and fitting[2]	17,400.00
	storage tank,8 tanks @ 20,000 gallons (accessories not included)[3]	800,000
Operational Cost	Electricity (yearly)[4]	29,565
	well maintenance and testing (yearly)[5]	$34,164
	Treatment (chlorine)[6]	$10,250
	Approximate PRASA Service (monthly)[7]	$22,000
	Total	$1,285,908

[*]Based on cost estimate for: 2004 provided by Campos Drilling (Campos, 2004); [2]2012 (Grainger, 2012); 2012 (Norwesco Tanks, 2012); [4] 2012 (AEE, 2012); [5] 2012 (Economic Co-operation and Development, 2012), [6]2012 year (Well Water Chlorination System Options, 2012) and [7] 2010 (PRASA, 2010).

6. Summary and Conclusions

The adequate management and development of groundwater resources requires a appropriate knowledge of the aquifer system well design (including wells location and production, wells connections, and operation and maintenance costs), and system constraints. It also requires the integration of large amount of spatial data and information, including the systems hydrogeology, land use, infrastructure, hydraulic properties, well dynamics, water use and demand. This integration can be done using GIS computational technologies, which also provide quick and “easy” tools for making decision for the management and development of groundwater system.

This work developed and applied GIS technologies, for the development of groundwater system in areas with existing water distribution infrastructure. The scope of the project focused in using a validation site at the University of Puerto Rico in Mayaguez (UPRM) to apply the methodologies developed.

The activities conducted in the study involved data collection and analysis, data integration to the GIS model, and application of the model to that validation site. Data collection included field testing, as well as available information and maps on the system’s physical characteristics (topography, land use), hydrogeology, aquifer characteristics, water use, water quality, and site’s infrastructure. Field testing involved aquifer and step drawdown tests to assess aquifer and well hydraulic characteristics. The data collected was analyzed and integrated into a hydrogeologic-water use model using GIS technologies. The model was subjected to system constraints to maximize the amount of potential groundwater supply, while minimizing impacts of groundwater development on aquifer depletion and water quality and optimizing system cost. Spatial constraints limited well location to areas available for development (e.g., open areas away from building, roads and other structures), and close to water distribution lines. Water extraction constraints limited total extraction to the amount of water replenish by aquifer recharge, and to maximum allowed drawdown at extraction wells.

The GIS model was applied to the UPRM validation site. Results from the field testing in this site generated the following observations and conclusion:

- The aquifer test at UPRM behaves hydraulically as a confined system. The hydraulic properties for the system resulted in 79,935 m^2/yr and 0.003 for average transmissivity and storage coefficients, respectively.

- The well system at UPRM is characterized by an average specific capacity of 24,717 m^3/yr-m (standard deviation= +/- 11,656 m^3/yr-m) per well, and an efficiency varying between 26.5 and 41.8% for extraction rates between 117,465 m^3/yr and 149,721 m^3/yr.

- Comparison between the estimated aquifer recharge (501,407-1,235,351 m^3/yr) estimated for the site validation and the water use (208,379 m^3/yr) suggests the system is able to provide the water use required by the UPRM site. Recharge rates, however, show high uncertainty and require for work for better understanding and more reliable results.

The well performance and general characteristics of the aquifer system at the validation site, were integrated in the GIS model to develop a well-field system which would satisfy water use requirements. The model allowed spatial visualization of the results for selection of potential areas for groundwater development and possible wells locations, determination of distance between wells and characterization of hydrogeological component useful in the aquifer recharge estimation.

The location of wells is determined from iterations of the GIS model according to the number of wells necessary to supply to water use. Initially the number of well is estimated by dividing the total water use by the specific capacity of wells (assumed to be the same for all wells). The potential location of wells determined with the GIS model relies on dividing the available area into subareas according to the number of wells needed. The number of subareas are set according to site-specific criteria. In the case of the UPRM validation site, the available area is subdivided into 5 subareas per additional well required. Once the subareas are generated with GIS, well locations are set within the subareas, and distance between wells determined. These distances are used to calculate total drawdown. Total drawdowns are calculated taking into account the drawdown caused by the pumping well on itself and on other wells. If drawdown exceeds total allowable drawdown constraints, well extraction rates are lowered, and the number of well recalculated based on new extraction rates and required demand. New locations of well and total drawdown are re-estimated. The process is repeated until all constraints are satisfied. Final location of wells was based on selecting the locations that maximize distance between wells and minimize connection distance to distribution system.

The establishment of the aquifer recharge as a constraint to determine the capacity of the system to provide the water use includes a sustainable element in the analysis that is important and commonly not considered. In addition, to minimizing aquifer depletion, the selection of the maximum allowable drawdown integrates a component to minimize damage and extend the life of pumping system.

Two scenarios were applied to the validation site to confirm that the suggested hydrogeological-water use model is functional in groundwater resources planning and development. The first scenario applied hydrogeologic and water use conditions. Results indicate that the groundwater system could provide the required water use for the validation site with two pumping wells (Figure 46). One well (existing CP well) is located in the Civil Engineering complex area, the other is located near to Business Administration Building (Figure 46). The wells would pump at a rate of 118,625 m^3/yr, which is lower than the maximum discharge that can be extracted from the well to meet the maximum allowable drawdown of 7m.

The second scenario, which applied a reduced specific capacity of 7,300 m^3/yr, required using more wells to satisfy the water use. Because of well interactions this scenario resulted in a higher total drawdown than allowed, and could not supply the required water use. The optimum groundwater development plan for this scenario (Figure 48) required 5 wells at a reduced pumping rate that would only supply 80% of the water use.

A third scenario was generated to supply water to specific building, areas of the validation site that are closer to the distribution system and maintain a high water use. This scenario indicates that the required water use for specific buildings can be supplied with 5 wells at a rate of 32,850 m^3/yr (90 m^3/day). All developed alternatives provided cost effective system that resulted in infrastructure capital gains with significantly lower investment and operational cost that what is being paid for comply with no aquifer depletion nor water quality impacts.

Results from the validation indicate that the GIS model and the methodology developed provide an efficient tool for intelligent design, development, and management of groundwater resources in areas with existing water infrastructure. The model provides a quick alternative to determining the feasibility of using the groundwater resources integrated with existing infrastructure as a water supply system. It combined analytical methods which are less expensive than numerical methods for performing groundwater analysis. Furthermore, the GIS tools provide an alternative to visualize the results and less time consumed in managing the data.

7. Future Work and Recommendations

Results from this research indicate that GIS technologies can be applied for intelligent design, development, and management of groundwater resources in areas with existing water infrastructure. The GIS-based model integrates water use, physical, hydrological and groundwater hydraulic characteristics, and constraints of the hydrogeological and water-supply infrastructure systems. The information and constraints applied must, however, be formulated for each particular site according to the criteria that must be met and the data and information available. Future work should consider the following tasks:

- Structure the GIS-developed model in a modular structure. The modular structure should allow for flexible data entry and constraint formulation, according to site-specific criteria.

- In regards to the analysis conducted at the UPRM validation site, further studies may be needed to include more information and validate or change simplifying assumptions. Particularly, the following tasks are recommended:

    - Acquiring more information on the hydrogeology of the site to better understand the aquifer system.
    - Conduct an aquifer recharge study to better estimate and quantify aquifer recharge and water balance.
    - Develop Numerical models (e.g., MODFLOW) to perform water budget analysis and further characterize the system.
    - Assess and integrate surface water/groundwater interactions.
    - Expand system constrains to include buffer areas near structures.
    - Integrate potential effects of pumping on ground settlement and effect on nearby structures.
    - Consider topography, soil characteristics, and water demand distribution in the system constraints.
    - Quantify the water demand for each building included in the area of study using a different method than the water meters measurements.

- Add future water demand and fire response water demand to the currently water demand estimates.
- Determine storage tanks location, water distribution analysis over the UPRM area.
- Consider additional costs for the well system and storage tanks that may include the pipeline connections to the wells, storage tank accessories, the operation costs, and water treatment costs.
- Perform additional water quality tests in order to determine other requirements for water treatment.

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Appendix A: Data Utilized for Water Budget Calculations

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Oct-00	0	81	1-Nov-00	0	79.5
2-Oct-00	0.1	80.5	2-Nov-00	1.43	79
3-Oct-00	0.12	80.5	3-Nov-00	0	80.5
4-Oct-00	0.7	80.5	4-Nov-00	0	79.35
5-Oct-00	0	79	5-Nov-00	0	79.3
6-Oct-00	0.6	79	6-Nov-00	0	77.5
7-Oct-00	0	79.5	7-Nov-00	0	79.5
8-Oct-00	0.06	80	8-Nov-00	0	82
9-Oct-00	0.01	80.5	9-Nov-00	0	82.5
10-Oct-00	1.16	79	10-Nov-00	0	80
11-Oct-00	0	79	11-Nov-00	0	78
12-Oct-00	0.12	80.5	12-Nov-00	0	78.8
13-Oct-00	0.01	80.5	13-Nov-00	0	78
14-Oct-00	0	80.5	14-Nov-00	0	78.5
15-Oct-00	0.309	80.05	15-Nov-00	0.14	80
16-Oct-00	0.13	80.5	16-Nov-00	0.74	77.5
17-Oct-00	0.8	80.5	17-Nov-00	0	78.5
18-Oct-00	0.52	80	18-Nov-00	0	78
19-Oct-00	0	79.5	19-Nov-00	0	75
20-Oct-00	0.65	79.95	20-Nov-00	0	79.5
21-Oct-00	0.12	78.5	21-Nov-00	0.1	78
22-Oct-00	0.12	79	22-Nov-00	0.18	78.5
23-Oct-00	1.84	77	23-Nov-00	0.24	78.5
24-Oct-00	0	79.5	24-Nov-00	0.05	78.5
25-Oct-00	0	80	25-Nov-00	0	75
26-Oct-00	0.05	82	26-Nov-00	0.29	78
27-Oct-00	0	80.5	27-Nov-00	0.06	77
28-Oct-00	0.01	81	28-Nov-00	0	77
29-Oct-00	0.12	81.5	29-Nov-00	0	77.5
30-Oct-00	0.3	80.5	30-Nov-00	0	79
31-Oct-00	0.01	78.5			

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Dec-00	0.91	78.5	1-Jan-01	0	76.5
2-Dec-00	0	78.5	2-Jan-01	0	76
3-Dec-00	0	79.5	3-Jan-01	0	75.5
4-Dec-00	0	79	4-Jan-01	0	75.5
5-Dec-00	0	78	5-Jan-01	0	76
6-Dec-00	0	76	6-Jan-01	0	77.5
7-Dec-00	0	77.5	7-Jan-01	0	77
8-Dec-00	0	79	8-Jan-01	0	75.5
9-Dec-00	0	79	9-Jan-01	0	75.5
10-Dec-00	0	78.5	10-Jan-01	0	75.5
11-Dec-00	0	79.5	11-Jan-01	0	75
12-Dec-00	0	81.5	12-Jan-01	0	75
13-Dec-00	0	82	13-Jan-01	0	74.5
14-Dec-00	0	79	14-Jan-01	0	75
15-Dec-00	0	80.5	15-Jan-01	0.03	75
16-Dec-00	0.057	76.5	16-Jan-01	0.75	75
17-Dec-00	0.057	76.4	17-Jan-01	0.57	75
18-Dec-00	0.2	76.5	18-Jan-01	0	75
19-Dec-00	0.43	75	19-Jan-01	0.14	74
20-Dec-00	0	77	20-Jan-01	0	75.5
21-Dec-00	0	76.5	21-Jan-01	0	75
22-Dec-00	0	75.5	22-Jan-01	0	75.5
23-Dec-00	0	76.15	23-Jan-01	0	74.5
24-Dec-00	0	76	24-Jan-01	0	76.5
25-Dec-00	0	76.05	25-Jan-01	0	76
26-Dec-00	0	76	26-Jan-01	0	73
27-Dec-00	1.38	78	27-Jan-01	0	80.5
28-Dec-00	0	77	28-Jan-01	0.01	81.5
29-Dec-00	0	75.5	29-Jan-01	0.12	82
30-Dec-00	0	75.5	30-Jan-01	0.3	80.5
31-Dec-00	0	75.85	31-Jan-01	0.01	78.5

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Feb-01	0	74.5	1-Mar-01	0	74.5
2-Feb-01	0.04	73	2-Mar-01	0	72
3-Feb-01	0.03	75	3-Mar-01	0	72.5
4-Feb-01	0.01	75	4-Mar-01	0	73
5-Feb-01	0	75	5-Mar-01	0	74.5
6-Feb-01	0	74.5	6-Mar-01	0	75.5
7-Feb-01	0	74.5	7-Mar-01	0	75.5
8-Feb-01	0	74.5	8-Mar-01	0	75.5
9-Feb-01	0	74.5	9-Mar-01	0	78
10-Feb-01	0.01	77	10-Mar-01	0	79
11-Feb-01	0	76.5	11-Mar-01	0	79.5
12-Feb-01	0	76.5	12-Mar-01	0	76.5
13-Feb-01	0	74.5	13-Mar-01	0	76
14-Feb-01	0	73.5	14-Mar-01	0	77.5
15-Feb-01	0	71	15-Mar-01	0	74.5
16-Feb-01	0	74	16-Mar-01	0.6	75
17-Feb-01	0	74	17-Mar-01	0	76
18-Feb-01	0	75.1	18-Mar-01	0	76.15
19-Feb-01	0	75	19-Mar-01	0	76.5
20-Feb-01	0	74.5	20-Mar-01	0	74.5
21-Feb-01	0	76.5	21-Mar-01	0.03	72.5
22-Feb-01	0.59	77	22-Mar-01	0.03	76.5
23-Feb-01	0	76	23-Mar-01	0	76
24-Feb-01	0.13	75.5	24-Mar-01	0	76.3
25-Feb-01	0.107	75.3	25-Mar-01	0	76.35
26-Feb-01	0.6	76	26-Mar-01	0	78
27-Feb-01	0	73	27-Mar-01	0	78
28-Feb-01	0	72	28-Mar-01	0	78.5
			29-Mar-01	0.2	77.5
			30-Mar-01	0.1	75.5
			31-Mar-01	0	76.55

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Apr-01	0	77.5	1-May-01	0	76
2-Apr-01	0	74.5	2-May-01	0	80
3-Apr-01	0.05	76.5	3-May-01	0	79
4-Apr-01	0.03	76	4-May-01	0	79
5-Apr-01	0.35	75	5-May-01	0	79.5
6-Apr-01	0.2	74	6-May-01	0	79.5
7-Apr-01	1.36	76	7-May-01	0.3	76
8-Apr-01	0.46	76	8-May-01	0	77
9-Apr-01	0.75	76.5	9-May-01	1	79.5
10-Apr-01	0	76.5	10-May-01	0.14	78.5
11-Apr-01	0	76.5	11-May-01	2.3	80
12-Apr-01	0	79.5	12-May-01	0.78	77.5
13-Apr-01	0	77	13-May-01	0	78
14-Apr-01	0.87	76.5	14-May-01	0	78
15-Apr-01	0.01	76.5	15-May-01	0.1	78.5
16-Apr-01	0	82	16-May-01	0	80
17-Apr-01	0	78	17-May-01	0	80.5
18-Apr-01	0	78.5	18-May-01	0	81
19-Apr-01	0	78.5	19-May-01	0.45	77.5
20-Apr-01	0	78	20-May-01	0	79
21-Apr-01	0.42	79	21-May-01	0	79.5
22-Apr-01	0.43	77.5	22-May-01	0	79.5
23-Apr-01	1.02	75	23-May-01	0	77.5
24-Apr-01	0.63	75.5	24-May-01	0	79
25-Apr-01	0.13	75.5	25-May-01	0	78.5
26-Apr-01	0	75.5	26-May-01	0	78
27-Apr-01	0.3	75.5	27-May-01	0	78
28-Apr-01	0	76.5	28-May-01	0	78.5
29-Apr-01	0.13	76	29-May-01	0	79
30-Apr-01	0.75	76	30-May-01	0	78.5
			31-May-01	0	79.5

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012).

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Jun-01	0.09	77	1-Jul-01	0.35	78
2-Jun-01	0.16	77	2-Jul-01	0	78
3-Jun-01	0.16	78.5	3-Jul-01	0	77
4-Jun-01	0	78.5	4-Jul-01	0	82.5
5-Jun-01	0	80	5-Jul-01	1.6	80.5
6-Jun-01	0.09	79.5	6-Jul-01	0	78.5
7-Jun-01	0	80	7-Jul-01	0	75
8-Jun-01	0	81.5	8-Jul-01	0.275	80.3
9-Jun-01	0	80.5	9-Jul-01	0.15	81
10-Jun-01	0	80.5	10-Jul-01	0	80.5
11-Jun-01	0.242	79.75	11-Jul-01	0.1	80
12-Jun-01	0.238	79.75	12-Jul-01	0	79.5
13-Jun-01	0.8	84.5	13-Jul-01	0.5	79.5
14-Jun-01	0	76.5	14-Jul-01	1.49	79
15-Jun-01	0	80.5	15-Jul-01	0	80.25
16-Jun-01	0.44	78.5	16-Jul-01	0	78.5
17-Jun-01	0	79	17-Jul-01	0	79.5
18-Jun-01	0.6	82	18-Jul-01	0.05	79
19-Jun-01	0	78.5	19-Jul-01	0.76	79
20-Jun-01	0	80	20-Jul-01	0	79
21-Jun-01	0	82	21-Jul-01	0	80.5
22-Jun-01	0	80.5	22-Jul-01	0	80
23-Jun-01	0.82	76	23-Jul-01	2.06	81
24-Jun-01	0.06	78.5	24-Jul-01	0	79.5
25-Jun-01	0.1	79	25-Jul-01	0.37	79.5
26-Jun-01	0.13	80	26-Jul-01	1.72	80.5
27-Jun-01	0	81	27-Jul-01	0.5	80
28-Jun-01	0	79.5	28-Jul-01	0	80
29-Jun-01	1.15	79.5	29-Jul-01	0.48	74.5
30-Jun-01	1.04	79	30-Jul-01	0.07	80.5
			31-Jul-01	0.9	79.5

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Aug-01	0	80	1-Sep-01	0.44	81
2-Aug-01	0.5	80	2-Sep-01	0.02	80.5
3-Aug-01	0.02	76	3-Sep-01	0	81
4-Aug-01	0	81	4-Sep-01	0.22	76.5
5-Aug-01	0	81	5-Sep-01	1.3	80
6-Aug-01	0.09	82.5	6-Sep-01	0	81
7-Aug-01	0	81	7-Sep-01	0	80.5
8-Aug-01	0	81.5	8-Sep-01	0.44	79
9-Aug-01	0.8	82.5	9-Sep-01	0.32	79
10-Aug-01	1.41	81	10-Sep-01	0	80.5
11-Aug-01	1.12	79	11-Sep-01	0.2	82.5
12-Aug-01	0.05	81	12-Sep-01	0.95	78
13-Aug-01	0	82.5	13-Sep-01	1	80.5
14-Aug-01	0	81	14-Sep-01	0.21	82
15-Aug-01	0	80	15-Sep-01	0.01	81
16-Aug-01	0	83.5	16-Sep-01	0.01	82
17-Aug-01	0	82	17-Sep-01	0	82
18-Aug-01	0.61	83	18-Sep-01	0.44	81.5
19-Aug-01	0.88	81	19-Sep-01	0	81.5
20-Aug-01	0	82	20-Sep-01	0.2	75.5
21-Aug-01	0	83.5	21-Sep-01	0.29	76.5
22-Aug-01	0	80.5	22-Sep-01	2.5	79
23-Aug-01	0	81.5	23-Sep-01	0.29	83.5
24-Aug-01	0	80	24-Sep-01	0.49	83
25-Aug-01	0	78	25-Sep-01	0.08	80.5
26-Aug-01	0.4	80	26-Sep-01	0.09	80.5
27-Aug-01	0.17	79.5	27-Sep-01	0.2	80.5
28-Aug-01	0.99	80	28-Sep-01	0.42	81
29-Aug-01	0	75.5	29-Sep-01	0	80.5
30-Aug-01	1.83	80	30-Sep-01	0.356	80.2
31-Aug-01	0.2	80			

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Oct-01	0	78	1-Nov-01	0	80
2-Oct-01	0	83	2-Nov-01	0.49	81.5
3-Oct-01	0	83.5	3-Nov-01	0	77.4
4-Oct-01	0.18	82	4-Nov-01	0	79.35
5-Oct-01	0	80.5	5-Nov-01	0	80.5
6-Oct-01	0.48	81.5	6-Nov-01	0.23	84.5
7-Oct-01	0	81.5	7-Nov-01	0.99	83.1
8-Oct-01	0	81.5	8-Nov-01	0.15	81.05
9-Oct-01	0	82.5	9-Nov-01	0.7	77
10-Oct-01	0	81.5	10-Nov-01	0.1	78.5
11-Oct-01	0.4	80.5	11-Nov-01	0	83
12-Oct-01	0.01	80.5	12-Nov-01	0	80.45
13-Oct-01	0	82.5	13-Nov-01	0	77
14-Oct-01	0.12	82.5	14-Nov-01	0.15	78
15-Oct-01	0	88	15-Nov-01	0.1	81
16-Oct-01	0	80.5	16-Nov-01	0	75
17-Oct-01	0	81	17-Nov-01	0.22	78.5
18-Oct-01	0	80	18-Nov-01	0	79
19-Oct-01	0.82	80	19-Nov-01	0	82
20-Oct-01	0	81.5	20-Nov-01	0	79
21-Oct-01	0	81	21-Nov-01	0	75.5
22-Oct-01	0.21	78	22-Nov-01	0	77.5
23-Oct-01	0.87	73.5	23-Nov-01	0	78.5
24-Oct-01	0.5	74	24-Nov-01	0	79.5
25-Oct-01	0.23	72	25-Nov-01	0	80
26-Oct-01	0	72	26-Nov-01	0	79.5
27-Oct-01	0.35	79	27-Nov-01	0	79.5
28-Oct-01	0.09	78.5	28-Nov-01	0	76
29-Oct-01	2	79.5	29-Nov-01	0	76
30-Oct-01	0.79	79.5	30-Nov-01	0	74
31-Oct-01	0	79.5			

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Dec-01	0	74	1-Jan-02	0	76.5
2-Dec-01	0	75	2-Jan-02	0	76.5
3-Dec-01	2	75.5	3-Jan-02	0	76.5
4-Dec-01	0	76.5	4-Jan-02	0	77.5
5-Dec-01	0	76.5	5-Jan-02	0	79.5
6-Dec-01	0	77	6-Jan-02	0	79
7-Dec-01	0	77.5	7-Jan-02	0	77.5
8-Dec-01	0.92	76.5	8-Jan-02	0	78
9-Dec-01	0.01	77.5	9-Jan-02	0	75.45
10-Dec-01	0.15	79	10-Jan-02	0	77
11-Dec-01	0.8	78	11-Jan-02	0	75.5
12-Dec-01	2.62	79	12-Jan-02	0	76.5
13-Dec-01	0.73	79	13-Jan-02	0.01	76
14-Dec-01	0	76	14-Jan-02	0	76
15-Dec-01	0	77	15-Jan-02	0	77.5
16-Dec-01	0.01	77	16-Jan-02	0	77.5
17-Dec-01	1.03	77.5	17-Jan-02	0	79.5
18-Dec-01	0.9	78.5	18-Jan-02	0	78
19-Dec-01	0	77.5	19-Jan-02	0	75.5
20-Dec-01	0	79.5	20-Jan-02	0	78
21-Dec-01	0	79	21-Jan-02	0	78
22-Dec-01	0	81	22-Jan-02	0	78
23-Dec-01	0	82	23-Jan-02	0	79
24-Dec-01	0.4	79.5	24-Jan-02	0	78
25-Dec-01	0	76.5	25-Jan-02	0	75.5
26-Dec-01	0	76.5	26-Jan-02	0	79
27-Dec-01	0	77	27-Jan-02	0	76.5
28-Dec-01	0	76.5	28-Jan-02	0	77.5
29-Dec-01	0	78.5	29-Jan-02	0	77
30-Dec-01	0	75.85	30-Jan-02	0	77
31-Dec-01	0	77.5	31-Jan-02	0	77.5

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Feb-02	0	77	1-Mar-02	0	77.5
2-Feb-02	0.06	76.5	2-Mar-02	0	75
3-Feb-02	0	76.5	3-Mar-02	0	74.5
4-Feb-02	0.24	76.5	4-Mar-02	0	79
5-Feb-02	0	74	5-Mar-02	0	80.5
6-Feb-02	0	80	6-Mar-02	0	80
7-Feb-02	0	76	7-Mar-02	0	75.5
8-Feb-02	0.11	76.5	8-Mar-02	0	76
9-Feb-02	0	76.5	9-Mar-02	0	79.5
10-Feb-02	0	77	10-Mar-02	0.01	79
11-Feb-02	0	79.5	11-Mar-02	0.71	77.5
12-Feb-02	0	77	12-Mar-02	0.3	75.5
13-Feb-02	0	77.5	13-Mar-02	0	74.5
14-Feb-02	0	76	14-Mar-02	0	75
15-Feb-02	0	74.5	15-Mar-02	0	74
16-Feb-02	0.05	74.5	16-Mar-02	0.11	75
17-Feb-02	0	73.5	17-Mar-02	0.45	76
18-Feb-02	0	77	18-Mar-02	0.1	76.5
19-Feb-02	0	75.5	19-Mar-02	0	78
20-Feb-02	0	75	20-Mar-02	0	79.5
21-Feb-02	0	74	21-Mar-02	0	78.5
22-Feb-02	0	75.5	22-Mar-02	0	77
23-Feb-02	0	72.5	23-Mar-02	0.113	76.3
24-Feb-02	0	74	24-Mar-02	0	77
25-Feb-02	0	75	25-Mar-02	0	77.5
26-Feb-02	0	78	26-Mar-02	0	78.5
27-Feb-02	0	74	27-Mar-02	0	76.5
28-Feb-02	0	77.5	28-Mar-02	0.79	78
			29-Mar-02	0.111	76.5
			30-Mar-02	0.111	76.5
			31-Mar-02	0.112	76.55

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Apr-02	0	78.5	1-May-02	0	77.5
2-Apr-02	0	78.5	2-May-02	0	79
3-Apr-02	0.53	77.5	3-May-02	0.29	78.5
4-Apr-02	0	77.5	4-May-02	0.4	76
5-Apr-02	0.24	80.5	5-May-02	1.31	76.5
6-Apr-02	2.42	78.5	6-May-02	0	78.5
7-Apr-02	1.5	76.5	7-May-02	0.22	78
8-Apr-02	0.33	79.5	8-May-02	0.85	78.5
9-Apr-02	0	79.5	9-May-02	0	76.5
10-Apr-02	0	75	10-May-02	0	77.5
11-Apr-02	0	73.5	11-May-02	0.21	78.5
12-Apr-02	0	74.5	12-May-02	0.219	78.55
13-Apr-02	0.02	75	13-May-02	0.71	78
14-Apr-02	0	75	14-May-02	0	78
15-Apr-02	0	78.5	15-May-02	0	78.5
16-Apr-02	0	76	16-May-02	0	79.5
17-Apr-02	1.15	78.5	17-May-02	0.35	79
18-Apr-02	0	78	18-May-02	0	79.5
19-Apr-02	0.53	79.5	19-May-02	0	79
20-Apr-02	0.28	78.5	20-May-02	0	79.5
21-Apr-02	0.9	78	21-May-02	0	79.5
22-Apr-02	0	79	22-May-02	0	79.5
23-Apr-02	0.83	79	23-May-02	0	82
24-Apr-02	0	78.5	24-May-02	0	81.5
25-Apr-02	0.21	78.5	25-May-02	0	79.2
26-Apr-02	0.3	78.5	26-May-02	0	79.2
27-Apr-02	0	77	27-May-02	0	78
28-Apr-02	0.28	81.5	28-May-02	0	82.5
29-Apr-02	0.14	75.5	29-May-02	0	80.5
30-Apr-02	0.48	77	30-May-02	0	82.5
			31-May-02	0	81

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Jun-02	0	83.5	1-Jul-02	0	80
2-Jun-02	0	83.5	2-Jul-02	0.05	80
3-Jun-02	0	82.5	3-Jul-02	0	81
4-Jun-02	0	81.5	4-Jul-02	0	81
5-Jun-02	0.12	78.5	5-Jul-02	0	81.5
6-Jun-02	0.99	80	6-Jul-02	0	77.5
7-Jun-02	0.11	80.5	7-Jul-02	1.21	79
8-Jun-02	0	81	8-Jul-02	0	79.5
9-Jun-02	0	81	9-Jul-02	0	81
10-Jun-02	0	80	10-Jul-02	0	81.5
11-Jun-02	0	80	11-Jul-02	0	81.5
12-Jun-02	0	81	12-Jul-02	0	80
13-Jun-02	0	80.5	13-Jul-02	0.273	80.3
14-Jun-02	0	82	14-Jul-02	0.279	80.3
15-Jun-02	0	81.5	15-Jul-02	0.3	79.5
16-Jun-02	0	80	16-Jul-02	0	81.5
17-Jun-02	0	81.5	17-Jul-02	0.09	82
18-Jun-02	0.15	84	18-Jul-02	0	80.5
19-Jun-02	0	77	19-Jul-02	0	80
20-Jun-02	1.63	80.5	20-Jul-02	0	80
21-Jun-02	0.75	77.5	21-Jul-02	0	80
22-Jun-02	0	79	22-Jul-02	0.1	80.5
23-Jun-02	0	80.15	23-Jul-02	0.49	80.5
24-Jun-02	0	81.5	24-Jul-02	0.2	79.5
25-Jun-02	0	80.5	25-Jul-02	0	79
26-Jun-02	0	81.5	26-Jul-02	0	80
27-Jun-02	0	82	27-Jul-02	0	82.5
28-Jun-02	0	80.5	28-Jul-02	0.13	84.5
29-Jun-02	0	82	29-Jul-02	0.19	82
30-Jun-02	0	81.5	30-Jul-02	0	84.5
			31-Jul-02	0	80.5

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix A- continued

Date	Precipitation (in)	Mean Temperature (F)	Date	Precipitation (in)	Mean Temperature (F)
1-Aug-02	0	81.5	1-Sep-02	0	83
2-Aug-02	0	81	2-Sep-02	0.6	81.5
3-Aug-02	0	80.25	3-Sep-02	0.6	80
4-Aug-02	0	80.25	4-Sep-02	0.8	82
5-Aug-02	0	77	5-Sep-02	1.2	82
6-Aug-02	0.9	81.5	6-Sep-02	0	81.5
7-Aug-02	0	82.5	7-Sep-02	0	80.35
8-Aug-02	0	82	8-Sep-02	0	81
9-Aug-02	0	83	9-Sep-02	0	83
10-Aug-02	1.9	82.5	10-Sep-02	0	83.5
11-Aug-02	0	82	11-Sep-02	0.1	83
12-Aug-02	1	82	12-Sep-02	0	81.5
13-Aug-02	0	81	13-Sep-02	0	81.5
14-Aug-02	0.61	81	14-Sep-02	0	81
15-Aug-02	0.72	80.5	15-Sep-02	0	81
16-Aug-02	0	80.5	16-Sep-02	0.39	81.5
17-Aug-02	0.95	78	17-Sep-02	0	81
18-Aug-02	0	82	18-Sep-02	0	81.5
19-Aug-02	0.69	81.5	19-Sep-02	0.48	78.5
20-Aug-02	0	81.5	20-Sep-02	0	81.5
21-Aug-02	0	82.5	21-Sep-02	0	82
22-Aug-02	0.15	83.5	22-Sep-02	0	81.5
23-Aug-02	0.01	80	23-Sep-02	0	81
24-Aug-02	0.292	80.3	24-Sep-02	0.1	81.5
25-Aug-02	0.297	80.3	25-Sep-02	0.03	82
26-Aug-02	0.41	80.3	26-Sep-02	0	79
27-Aug-02	0.61	77.5	27-Sep-02	0	80
28-Aug-02	0	80.5	28-Sep-02	0	80.5
29-Aug-02	0	82	29-Sep-02	0	80
30-Aug-02	0	81	30-Sep-02	0	82.5
31-Aug-02	0.5	78			

Note: Yellow cells represent missing values that were filled out using average data for precipitation and/or temperature values (The Southeast Regional Climate Center, 2012)

Appendix B: Materials and Equipments

Figure 50: Water level meter

Figure 51: Levelogger device

Figure 52: Pumping Well located at Department of Civil Engineering and Surveying

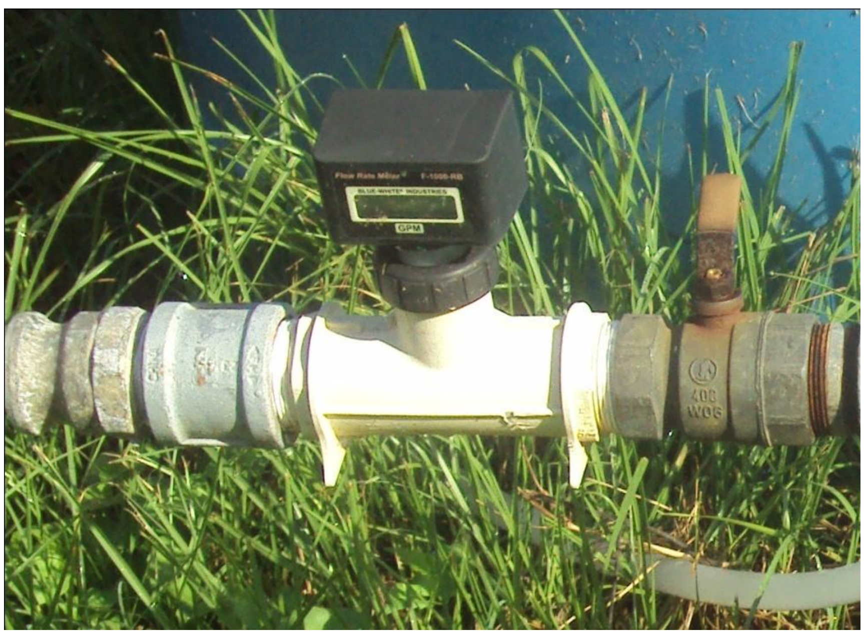

Figure 53: Flow meter utilized to estimate flow rates at the pumping well

Appendix C: Water Level and Drawdown Measurements

Water level meter is an instrument which measures the depth of the water from the reference point (match point or land surface). This measure is known as the depth to water below the match point or surface land (h_{dw}). Figure 54 shows the different depth to water level measurement used for calculating the water level (h) above the mean sea level (asl) after using the following equations.

$h_{sl} = h_{dw} – h_{mp}$

h = surface elevation (asl) - h_{sl}

where:

h_{sl} = depth to water from the land surface to the water level [length],

h_{dw} = depth to water from the match point to the water level [length],

h_{mp} = math point height [length], and

h = water head elevation (asl) [length].

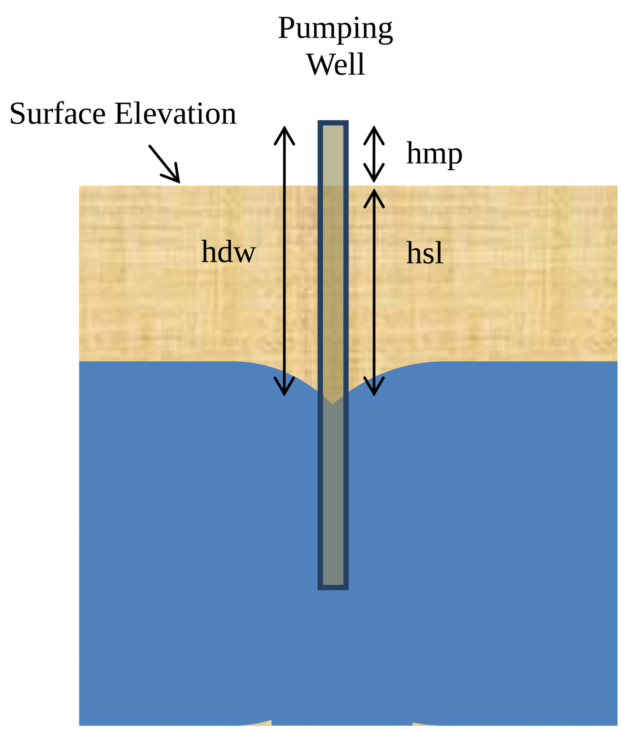

Figure 54: Image showing the depth to water used for calculating the water level (asl)

Drawdown is calculated over time after pumping by subtracting the measured water level over time after pumping from the initial water level (Figure 55). The temporal distribution of drawdownsare used to perform aquifer analysis and determine transmissivity and storage coefficients.

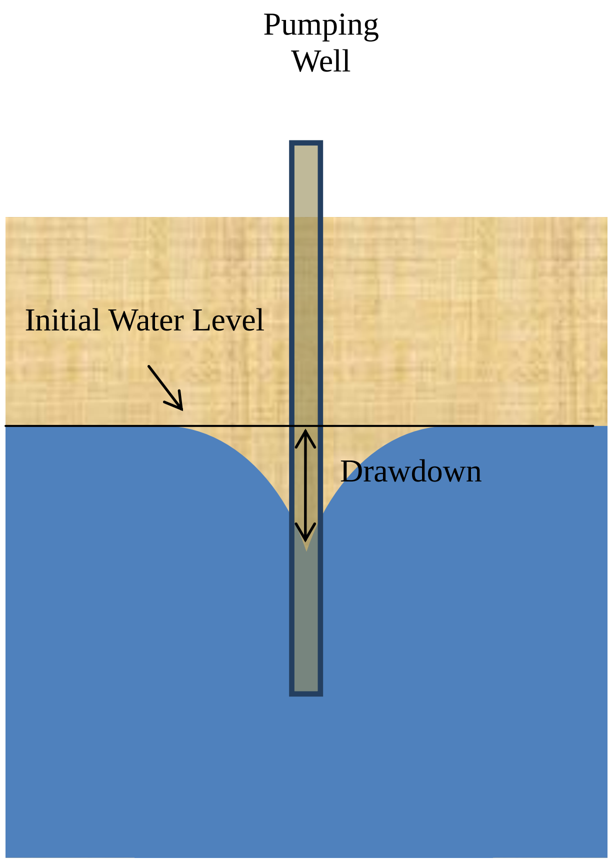

Figure 55: Drawdown diagram

Appendix D - UPRM Water Consumption for 2009 and 2010 (PRASA, 2011)

2009	Finca Alzamora	Biología	Física	Química	Complejo de Ingeniería	Fuente La Vita	Piscina Principal	CID
Jan-09	118	2,737	3,003	1,304		1,169		155
Feb-09		1,836	1,935	843	52	1,116		
Mar-09			3,904	3,498		1,116		119
Apr-09	200		4,238	2,947	3,916	1,483	379	305
May-09			4,204	1,532	637		104	261
Jun-09	1,485	10,697	3,032	1,113	831	1,567	104	160
Jul-09	2,213	6,991	2,441	1,107	832		135	160
Aug-09	65	8,958	2,780	1,379	700	1,855	197	200
Sep-09	4,231	4,127	2,512	1,094	536		4,728	221
Oct-09	1,953	4,739	3,563	1,579	696	1,412	4,943	0
Nov-09	1,460		2,947	1,433	510	706	3,904	180
Dec-09	1,543	7,005	4,035	1,290	581	1,423	6,744	147

2010	Finca Alzamor a	Biología	Física	Química	Complejo de Ingeniería	Fuente La Vita	Piscina Principal	CID
Jan-10	2,258	12,286	3,150		765		3,798	374
Feb-10								292
Mar-10	1,637	6,262	3,933	1,159	574		4,011	636
Apr-10	1,903	7,799	3,722	1,232	516	1,489	34,513	200
May-10	2,027	6,565	4,425	1,228	449		3,792	150
Jun-10	1,730	6,212	3,427	1,254	328	2,062	4,133	125
Jul-10	1,905	8,841	46	1,042	452	1,654	21,248	
Aug-10	2,029	7,761	2,135	977	615		3,926	150
Sep-10	683	5,349	2,046	716	385	1,558	4,314	227
Oct-10	237	10,490	3,297	1,318	912		4,148	150
Nov-10	1,300	6,650	2,335	976	457		3,259	204
Dec-10		6,853	4,216	1,719	974		3,231	177

Appendix E: UPRM Water Distribution Layout and UPRM Buildings Layout

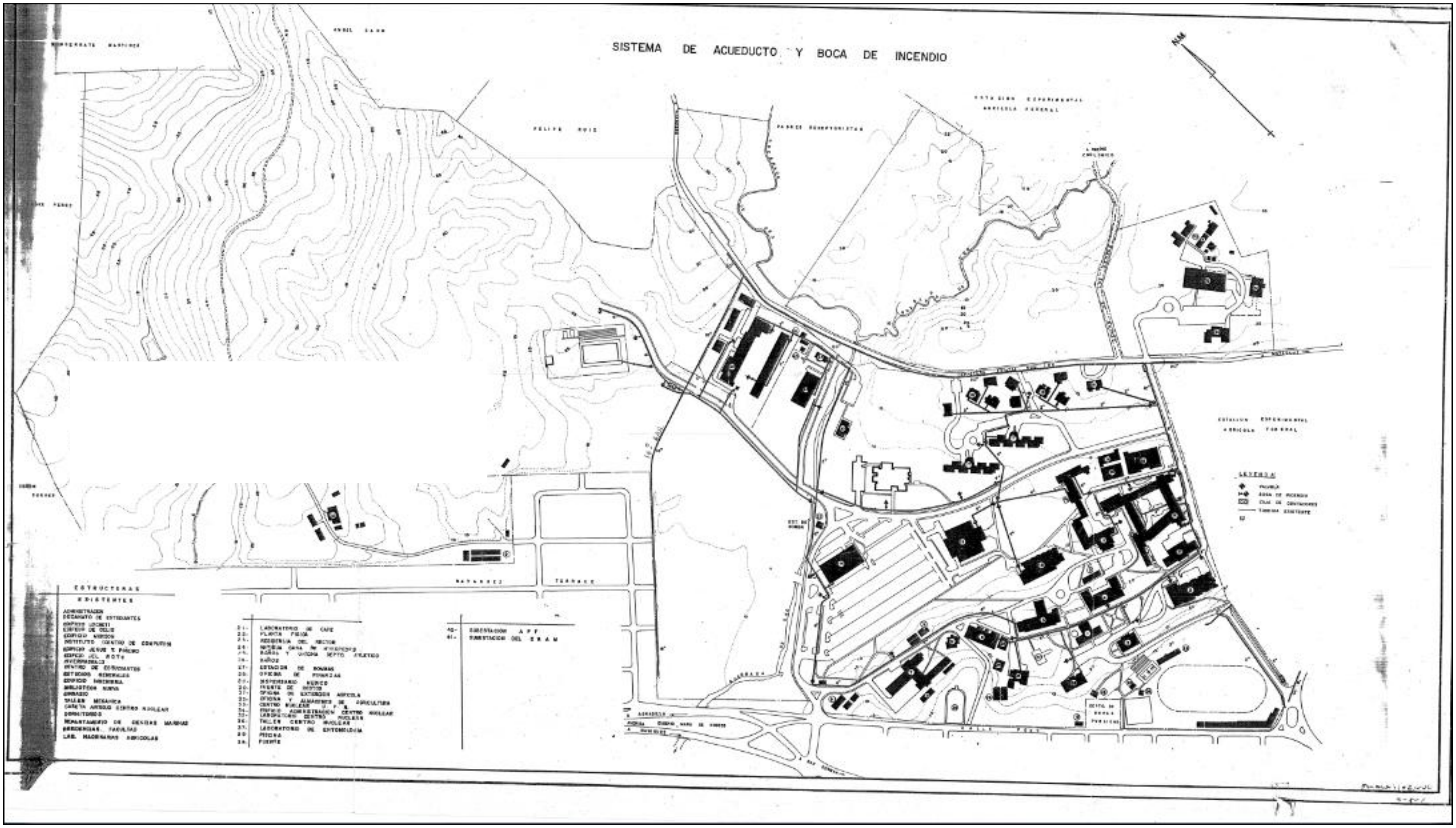

Figure 56: UPRM layout showing part of the water supply distribution system

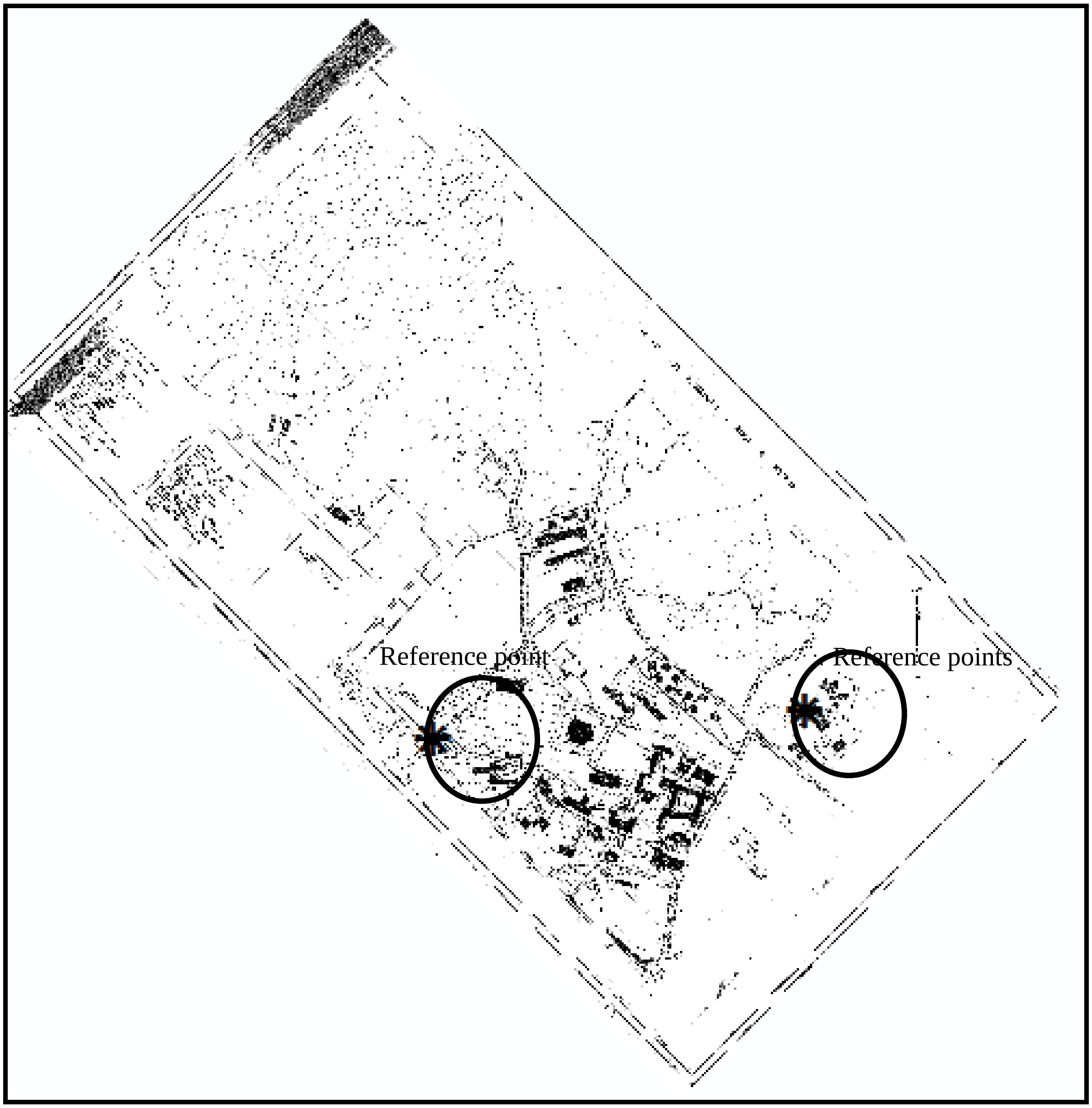

Figure 57: UPRM water distribution system layout after georeferencing using ArcGIS tool (asteric symbols representing reference points (Table 4))

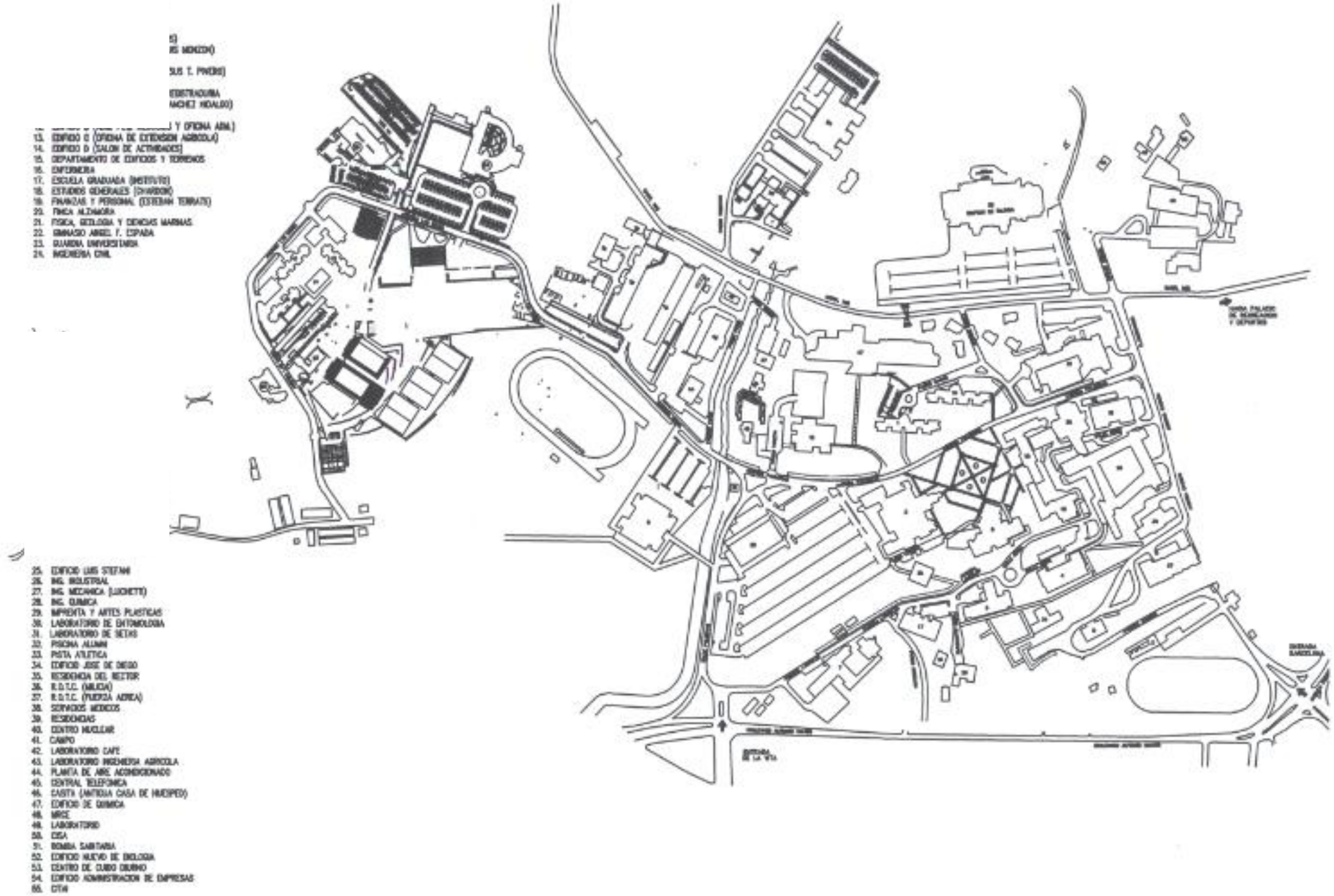

Figure 58: UPRM current layout used for complete the water distribution network

Figure 59: Current UPRM layout after georeferencing using ArcGIS tool (asteric symbols representing reference points (Table 4))
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Appendix F: CP Well Unit Cost

NOV-29-2004 15:22 FROM: 7877200180 TO:17872655390 P.2

Perforaciones E. Campos, Inc.

Contratistas de Pozos Profundos para agua, Bombas y Pruebas de Bombeo

Cotización: 291104-200

29 de Noviembre de 2004.

Universidad de P.R.
Recinto Universitario de Mayagüez
Departamento de Ingeniería
P.O. Box 9041
Mayagüez, P.R. 00981

Atención: Dra. Ingrid Padilla

Bomba

1. Bomba para 75 GPM, 5 HP, monofásica, con su motor Franklin, caja de control, etc.........$3,000.00
2. 80' pies de tubería de 2" plgs 80' X $3.00.........240.00
3. Cable sumergible # 10/3 100' X $2.00.........200.00
4. Tapa de Pozo.........60.00
5. Instalación del sistema hasta la salida del pozo.........900.00

Costo de la Bomba:$4,400.00

Ernesto Campos

La Muda Contract Branch, Caguas, Puerto Rico 00725 · Carr. #1, Km.24.3, Barrio Buen Pastor · Tel. (787) 789-1288, Fax (787) 720-0180

Received Time Nov.29. 2:59PM

Figure 60: CP well cost including pump, pipes, cables, well top and the well installation